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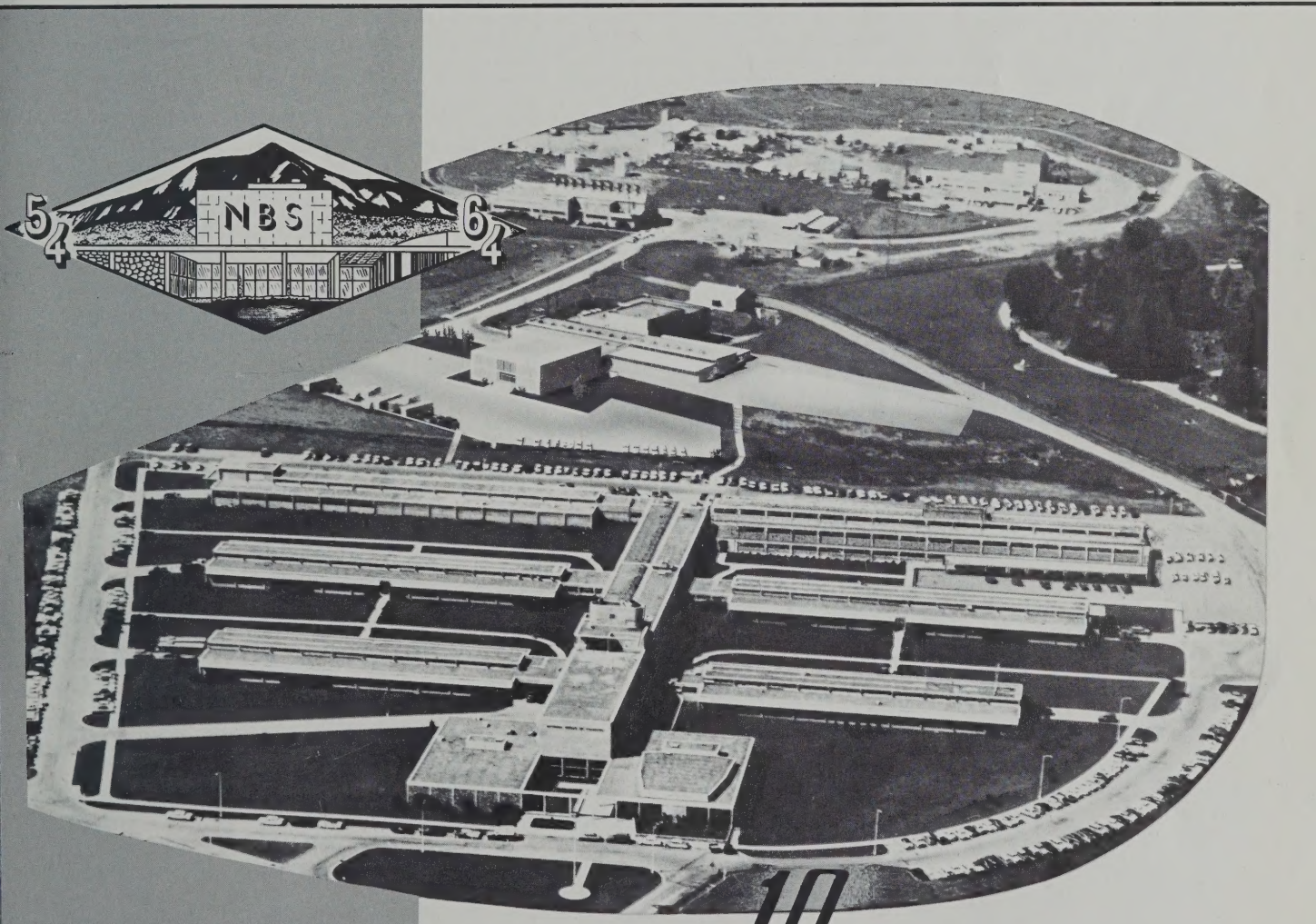

10th Anniversary

BOULDER LABORATORIES

U.S. DEPARTMENT OF COMMERCE — LUTHER H. HODGES, *Secretary*

NATIONAL BUREAU OF STANDARDS — A. V. ASTIN, *Director*

NATIONAL BUREAU OF STANDARDS

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COVER: Air view of the NBS Boulder Laboratories, Boulder, Colo. Principal buildings are Radio (*foreground*), Main Cryogenics (*center*), and Liquefier (*left center background*). Other buildings house small laboratories or service facilities. The Radio Building is occupied by the Central Radio Propagation Laboratory and the Radio Standards Laboratory. The Cryogenic Engineering Laboratory occupies the Main Cryogenics and the Liquefier Buildings.

THE WHITE HOUSE

WASHINGTON

July 29, 1964

I congratulate the Boulder, Colorado, Laboratories of the Commerce Department's National Bureau of Standards on the completion of ten years of valuable service to the Nation.

In the pioneer spirit of the West, this government research laboratory has advanced the frontiers of knowledge in radio science, electronics, and low temperature engineering. The effects of your work on the broad fields of radio and electronics, on the exploration of space, and on securing the peace have yielded great benefits to Government, industry, and the Nation as a whole.

May the next ten years bring even greater achievements from the dedicated staff of this scientific institution.

My best wishes at this proud moment in your history.

Lyndon B. Johnson

TEN YEARS OF PROGRESS

NBS Boulder Makes Strides in First Decade

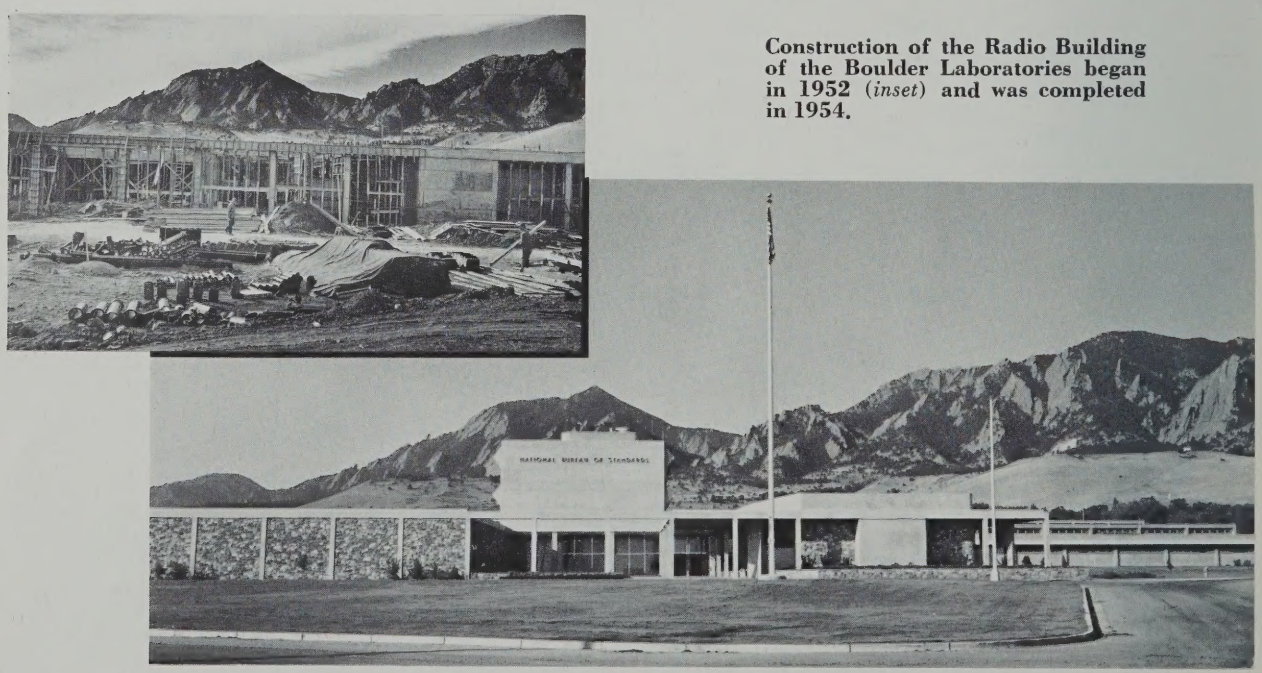
"IT SEEMED to me, as I went through these laboratories, that here we have a new type of frontier . . . . The frontier days when we could discover new land, new wonders of geography and of nature, have been largely in the past. Here today we have a frontier of possibly even greater romantic value, as well as greater material value to us, than were some of the discoveries of those days." Thus spoke President Eisenhower at the dedication of the NBS Boulder Laboratories in September 1954. His remarks were particularly appropriate to the occasion as NBS had been engaged in pioneering work in radio continuously since 1909 and the Boulder site had been specially chosen to provide a suitable location for further pioneering research in this field.

Boulder was to become the new home of the NBS Central Radio Propagation Laboratory (CRPL), which had been established shortly after World War II to concentrate Federal research and services on radio wave propagation within a single organization. Within a few years CRPL had outgrown the small Radio Building on the Bureau grounds in Washington and it was decided to move the Laboratory to Boulder because of the geographical and topographical advantages of that area for radio propagation studies. Here the climate allows year-round field work and the varied terrain makes it possible to use a wide variety of transmitter and receiving station arrangements.

Construction of the new radio building had not yet begun, however, when a need arose for a low-temperature (cryogenic) engineering laboratory to provide the large quantities of liquefied gases needed in the development of the hydrogen bomb, and this laboratory was also placed on the Boulder site. Thus the dedication in 1954 found two NBS laboratories located at Boulder: the Cryogenic Engineering Laboratory and the Central Radio Propagation Laboratory, which at that time included work on both radio propagation and radio standards. Later the work on radio standards was split off from CRPL to become the Radio Standards Laboratory. At the time of the dedication the staff of the Boulder Laboratories numbered about 350 persons, many of whom had recently transferred from the Washington laboratories.

Moving laboratory and office equipment from Washington was a gigantic task, requiring dozens of vans. A few very delicate pieces of equipment were shipped by air, including an item with perhaps the greatest intrinsic value of any that was moved—the U.S. standard of frequency and time interval. This standard consisted of a group of extremely stable quartz crystals which had to be operated continuously in an electrical circuit at constant temperature, pressure, and relative humidity.

Some of the crystals from the group were left in operation in Washington while the remainder were brought to Boulder and stabilized. The National standard remained temporarily in Washington, provided by the crystals left behind. In the meantime, those brought



Construction of the Radio Building of the Boulder Laboratories began in 1952 (*inset*) and was completed in 1954.

to Boulder were placed in operation and compared daily with the standard, using NBS radio station WWV as the link between Boulder and Washington. Several months later, when careful measurements indicated that the Boulder crystals were stable and operating satisfactorily, they were made the standard. The transfer of this basic standard, begun in April, was completed in October with the arrival of the final units from Washington.

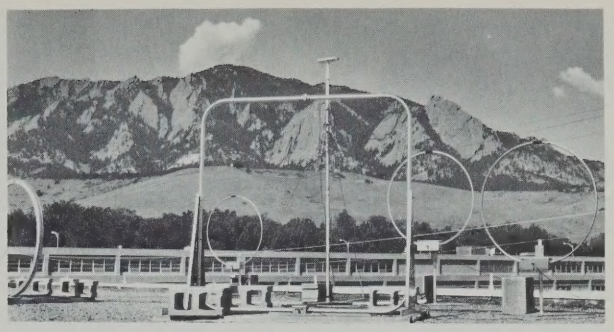
Boulder is now the Nation's center for precision measurements of radio frequency and time interval. The U.S. Frequency Standard, however, is no longer a quartz-crystal standard but a cesium-beam atomic standard capable of a precision of 2 parts in 10^{12} and an accuracy of 1 part in 10^{11}. (Quartz crystals are still part of the U.S. Working Frequency Standard.)

For many years the Bureau has been investigating atomic standards of frequency and time as part of its program for relating basic standards of measurement to constants of nature. An ammonia frequency standard had been completed and a cesium-beam model constructed before the move from Washington. At Boulder the effort was concentrated on the cesium-beam principle. In 1960, when two models had been completed, compared, and thoroughly evaluated the cesium-beam standard was adopted as the U.S. Frequency Standard. Research to develop an even more precise frequency standard is under way.

The standard frequencies and time signals are now being transmitted to users by four NBS radio stations: WWV, Beltsville, Md. (near Washington, D.C.) and WWVH, Maui, Hawaii, both of which are high frequency; and, at Fort Collins, Colo., WWVB (low frequency, 60 kHz) and WWVL (very low frequency, 20 kHz). Of these, only WWV and WWVH were in operation in 1954. WWVL and WWVB, which began broadcasting from their permanent location near Fort Collins in the summer of 1963, are phase-locked to the U.S. Working Frequency Standard at Boulder through microwave transmission. WWV in turn is controlled by the transmissions of WWVL.

Pioneering research on a radically new mode of radio propagation known as forward scatter had been under way at CRPL for several years before the move to Boulder. This work was continued after the move, and the results of the program have been so successful that scatter circuits are now in use in many parts of the world. Because of the unusual phenomena associated with auroral disturbances that relate to forward scatter, experiments are continuing in both arctic and antarctic locations. This year a new antarctic network of three transmitting and six receiving stations was placed in operation.

Although the basic objective of the work of CRPL is to improve the quality of radio communication insofar as it is affected by the transmission media and by noise and interference effects, the investigations required to meet this objective have led to basic studies of the upper and lower atmosphere, of the sun, of relationships between phenomena on the sun and in the earth's atmosphere, and of planets and stars that are emitting radio energy. Such basic studies involve extensive observations on a worldwide scale using both radio and optical techniques. A network of field stations for this purpose extends from the poles to the tropics. Some are operated by NBS; others furnish data on a contract or exchange basis.



Loop antennas and a ferrite-type antenna (*on pole*) used in monitoring LF and VLF standard frequency and time broadcasts from GBR, Rugby, England; CYZ40, Canada; NBA, Balboa, C.Z., and the Bureau's stations WWVB and WWVL, Fort Collins, Colo.

In 1954 the hydrogen liquefier in the new Cryogenic Engineering Laboratory was the largest in existence; now it is dwarfed by plants producing liquid hydrogen in commercial quantities. However, many problems in large-scale production of liquefied gases were first worked out in the Bureau's pioneer plant. An important advance was the perfection of a catalytic method for converting unstable ortho-hydrogen to stable para-hydrogen in the liquefier. This development made possible the production, storage, and shipping of large quantities of liquid hydrogen without appreciable loss of liquid.

Other work resulted in a mineral-powder insulation which greatly enhances the insulating qualities of the liquefied-gas containers. Large tank trucks with capacities of thousands of gallons of liquid hydrogen or liquid helium now employ this type of insulation, with a great reduction in size and much simpler construction.

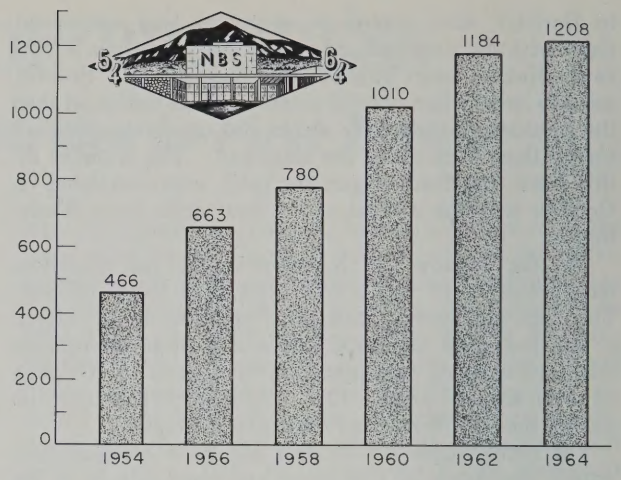
In 1962 a new concept in NBS cooperative programs was introduced when, in conjunction with the University of Colorado, the Joint Institute for Laboratory Astrophysics was established on the University campus at Boulder. JILA is a unique organization devoted to laboratory research and theoretical investigations in astrophysics, rather than to the acquisition of data through astronomical means such as observatories, rockets, and balloons. The Institute has a small permanent staff of NBS and University personnel, but brings together scholars from many fields of physics and astrophysics in a center for advanced research and training of graduate and postdoctoral students.

In January 1964 the Bureau was reorganized and subdivided into four institutes in order to provide better services to science and industry. CRPL then became one of the new institutes without change in its name, the Radio Standards Laboratory and the NBS staff members at JILA became part of the Institute for Basic Standards, and the Cryogenic Engineering Laboratory became part of the Institute for Materials Research.

In the ten years of its history the Boulder Laboratories has experienced a steady growth, both in program and personnel. The total staff is now approximately 1,500 and the physical plant has also been enlarged. Two wings have been added to the Radio Building, one occupied by the Electronic Calibration Center (a part of the Radio Standards Laboratory) in 1958, the other by the Computation Facility in 1962. An addition to the Cryogenic Laboratory Building was completed in July of this year. Advance planning is under way for a Radio Standards Building.

As part of the dedicatory program in 1954, two scientific conferences were held—one on radio propagation and the other on cryogenic engineering. Thus began a long series of conferences and symposia. Not the largest, but perhaps the most significant and certainly the most important internationally, was the XIIth General Assembly of URSI in the summer of 1957, sponsored jointly by NBS, the University of Colorado, and the City of Boulder.

The cryogenic engineering conferences, the first of which in 1954 had an attendance of 200, eventually became so large that the Boulder Laboratories could no longer accommodate them. The Fourth Conference on Precision Electromagnetic Measurement attracted more than 600 participants in June 1964. Two Very-Low-Frequency Symposia have been held, and the National Center for Atmospheric Research joined NBS as co-host for the Ultra-Low-Frequency Symposium in August.



FULL-TIME PERMANENT STAFF, NBS BOULDER LABORATORIES

In the following pages the more significant achievements of the Boulder Laboratories over the last decade are summarized in somewhat greater detail for CRPL (p. 162), the Radio Standards Laboratory (p. 154), and the Cryogenic Engineering Laboratory (p. 148). In addition, some of the most recent accomplishments of these laboratories are described in separate articles.

CRYOGENIC ENGINEERING

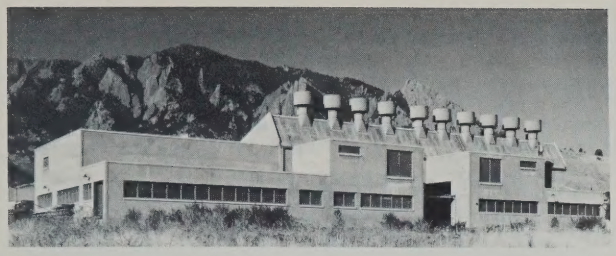
ON JULY 1, 1954, the Cryogenic Engineering Laboratory (CEL) was organized as a division of the Boulder Laboratories. At that time the staff numbered 40. Ten years later, at the end of the fiscal year 1964, there were 92 full-time employees, and the Cryogenic Engineering Laboratory was recognized as a major center of low-temperature research.

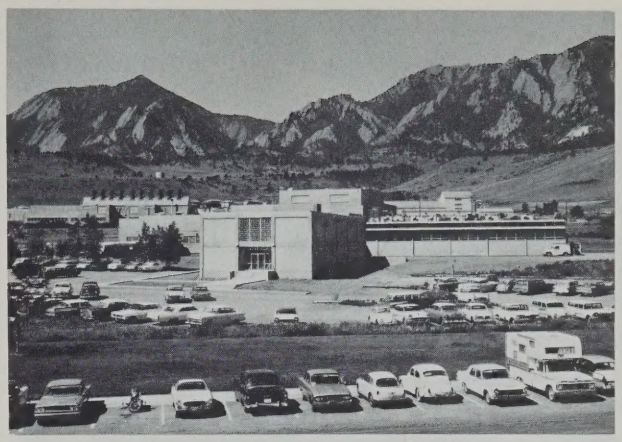
The growth of CEL as a major division of the National Bureau of Standards reflects the increasing importance of low-temperature technology to our Nation's economy. The temperature limits of cryogenics have not been precisely defined, but the word itself derives from the Greek *kryos*, referring to extremely low temperatures, and usually means temperatures below 150 °K. Cryogenics is often regarded as a means to operations which either cannot be done at room temperature or can be done better at low temperature.

Common gases become liquids at cryogenic temperatures, with a resulting volume reduction of several hundredfold. The high-density, low-bulk form of liquefied gases has suggested a multitude of applications. The natural gas industry has recognized and employed the technique to gain economies in transportation and storage. Hospitals are capitalizing on the compact storage of breathing oxygen in liquid form. Hydrogen is a high-energy fuel with maximum potential thrust for the rocket engines of space vehicles. Steel mills use hundreds of tons of liquid oxygen daily to provide a concentrated oxidizer to the fires in their blast furnaces.

Liquefied gases are finding an increasing variety of uses as refrigerants. Plumbers are using liquid nitrogen to freeze pipelines temporarily while modifying sections of water distribution systems. The fact that cryogenic temperatures can cause cellular death is being used in neurosurgery and in removal of warts. On the other hand, the medical profession is using liquid-nitrogen temperatures to preserve spermatozoa and blood for periods longer than was previously possible. Scientists use cryopumping (condensation of gases on a cold surface) to achieve vacua hitherto impossible to attain. By cooling the coils of an electromagnet with cryogenic fluid, high magnetic fields can be produced with low power input. Bubble chambers and neutron moderators are new tools of science made possible by advanced cryogenic systems.

Low-temperature research has been a function of the National Bureau of Standards almost since its inception in 1901. It is mentioned in the NBS annual report of 1902. In 1904 the Bureau fell heir to a hydrogen liquefier which had been among the scientific exhibits at the World's Fair held that year in St. Louis. A separate low-temperature laboratory in the Heat and Power





Above: **The first building on the Boulder Laboratories site was the Liquefier Building, completed in 1951 to house large-capacity nitrogen and hydrogen liquefaction plants of the Cryogenic Engineering Laboratory.** *Right:* **Most recent construction at the Boulder Laboratories was an addition to the Main Cryogenics Building, which practically doubled its floor area. The new construction was occupied July 20, 1964.**

Division is first mentioned in the annual report of fiscal year 1914. In the years that followed, the Bureau developed a unique capability in cryogenic technology.

In 1950 the Atomic Energy Commission (AEC) asked the Bureau to design and construct a hydrogen liquefier several times larger than any in existence at that time. In 1952 the liquefier and research laboratory were commissioned on the Boulder site. The liquefier was developed under a very abbreviated time schedule, and the principal staff contributing to its design and operation received the Department of Commerce Exceptional Service Award.

In the early 1950's a group of scientists from CEL and the Washington laboratories succeeded in developing a highly effective catalyst for the conversion of normal liquid hydrogen to parahydrogen. Normal hydrogen is a mixture of two different forms, one—the ortho—having an unstable molecular structure, the other—the para—being stable. When normal hydrogen is liquefied, the ortho form changes naturally to the stable para form, with a release of heat. As a result, some of the liquid hydrogen is evaporated. Development of a catalyst that completes this conversion process in the liquefier made it possible to save liquid hydrogen that otherwise would have been lost by unavoidable vaporization. The saving has been enormous. Tonnage hydrogen liquefiers using the catalysts proposed by CEL are now commonplace.

Precision measurements of the thermal properties of parahydrogen from the triple point to ambient temperature and at pressures up to 340 atm have been made at CEL. The resulting map of hydrogen properties is vital to engineers and scientists engaged in the design of equipment and processes needed for hydrogen applications.

Research at CEL has established design parameters for hydrogen-distillation columns used to produce deuterium. The results have provided a basis for column designs in several foreign countries.

An aluminum magnet, cooled with liquid hydrogen, has been devised and built by a team of scientists and engineers at CEL. It produces fields in excess of 9 T (90,000 G) with the expenditure of only 18 kW of electrical power. The magnet produces a field uniform to 1 percent over a 2.5-cm-diam sphere, and the actual working space is 6 cm in diameter.

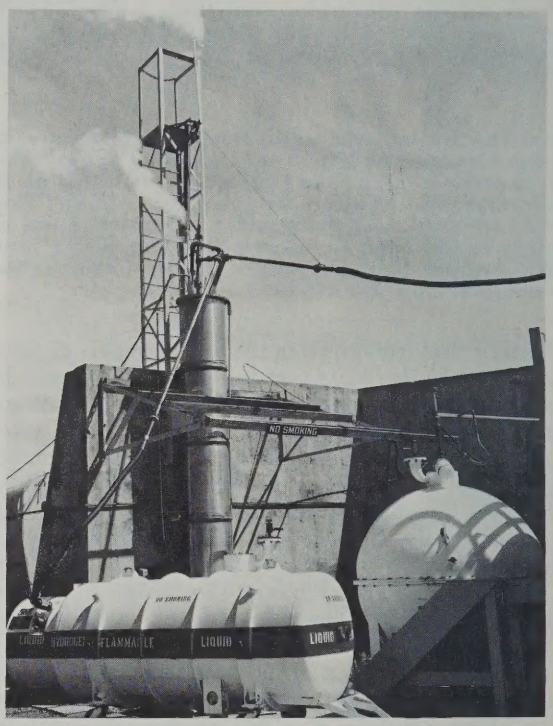
In the last decade, interest has been focused primarily on the technology and uses of liquid hydrogen. It is apparent that this interest is now shifting, and the technology and uses of liquid helium will become of greater importance. In 1957, CEL pioneered in the transportation of liquid helium by airplane. In the years that followed, helium liquefied at CEL in Boulder was shipped by air to the NBS Washington laboratories to support the free-radicals research program. Extensive study of helium liquefaction and transportation at CEL provided basic information vital to the use of liquid helium as a refrigerant during the ground cooldown of the hydrogen-oxygen engine of the Centaur missile. The helium was supplied by air shipment from commercial plants.

To date, CEL staff members have prepared 327 publications and have been awarded eight patents. Russell B. Scott, now Manager of the NBS Boulder Laboratories and formerly Chief of CEL, is the author of a textbook, *Cryogenic Engineering* (D. Van Nostrand Co., Inc., Princeton, N.J., 1959). It is an authoritative text that is widely recognized for its completeness and clarity. The Soviet Union has recently published a Russian translation of Mr. Scott's book.

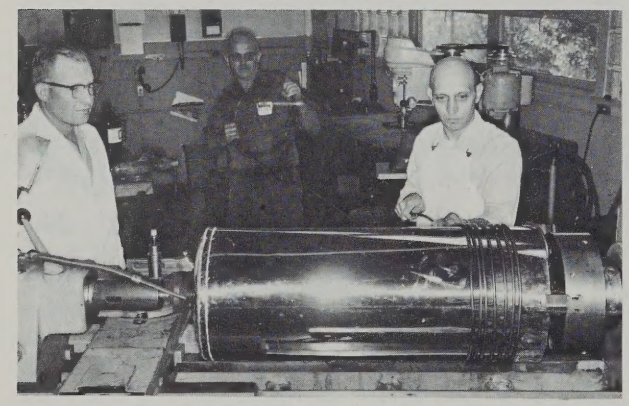
In September of 1954, CEL sponsored the first Cryogenic Engineering Conference. The Conference was held at Boulder as a part of the scientific meetings at the time of the dedication of the NBS Boulder laboratories; about 200 delegates attended. The Conference is now held annually under the direction of an independent committee and is sponsored by several organizations. Attendance at individual Conferences has exceeded 1,000, with as many as 60 delegates coming from foreign countries.

CEL furnishes advisory, coordinating, and consultative services on low-temperature problems to other Government agencies and to the public. These services provide specific technical information to organizations outside the Bureau in support of activities involving cryogenic systems. The advisory service may be an on-the-spot answer to an informal telephone call, or the request may require hundreds of hours of service. One

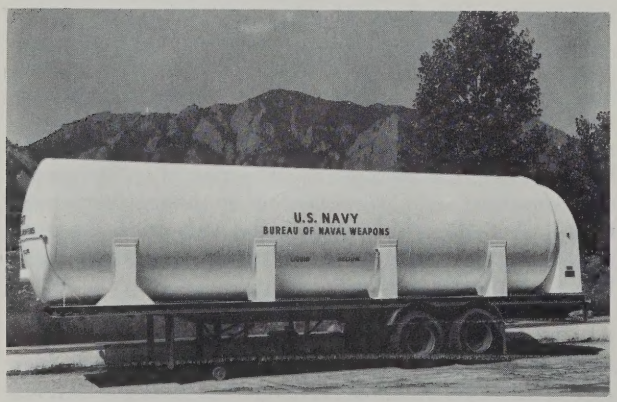
Left: **Thin-film samples are prepared for research on fundamental properties of superconductors by vaporizing the metal onto sample holders. Properties of superconductors, particularly magneto-resistivity, change radically with a change in one dimension. Better materials for the windings of superconducting electromagnets is an objective.**

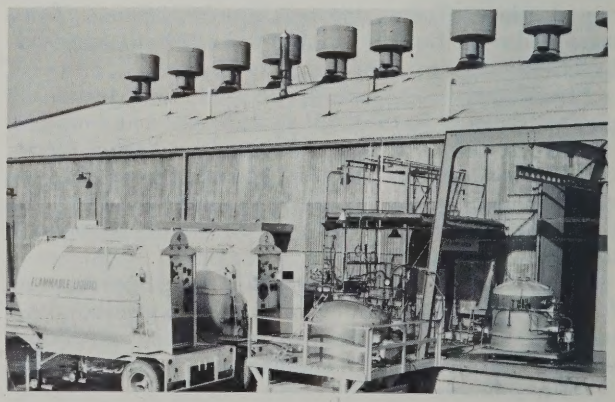


Above: **Evaporative cooling of liquid hydrogen by the bubble-through of helium gas, experimentally investigated by CEL, was used by NASA to prevent cavitation in the supply line to the motor of the Saturn I second-stage engine during the pre-launch period at Cape Kennedy in January 1964.**



Left: **Laboratory mechanics fabricate special equipment not otherwise available for unique projects at CEL. Skilled shop personnel wind a refrigeration coil from annealed copper tubing.**





Left: **Research on insulation of Dewars facilitated the design and construction of large-capacity transport trailers used for liquid hydrogen and liquid helium.** *Right:* **Liquid hydrogen for laboratory use is stored in small Dewars** (*center and right*) **located outside the Liquefier Building. Distribution to laboratories is made in 6,000-liter Dewar trailers.**

such project was assistance to the bubble chamber installation at the University of California's Lawrence Radiation Laboratory.

In 1958, in response to the need for preparation and dissemination of technical information to cryogenic engineers, a Cryogenic Data Center was established by CEL. The Data Center supplies new data from CEL and other cryogenic research centers, not only to the CEL staff, but also to the general technical public. Since its establishment, the Data Center has been steadily strengthened to provide the essential service of compilation and dissemination of cryogenic engineering data. Information is exchanged internationally by coordinating with groups throughout the world.

Professionals at the Data Center evaluate and compile data on the properties of materials at low temperatures. These data are put into the form of charts, compendia, and technical reports for dissemination. More than 1,200 documents per year are acquired for review and selection of data.

Approximately 4,000 persons and companies are served regularly by the Data Center. Last year over 20,000 copies of some 350 CEL publications and charts were distributed in response to about 2,000 requests. In addition, the Center provided bibliographic information on source material to the CEL staff and outside requestors. More than 6,000 articles of cryogenic interest were noted in the world literature and coded for bibliographic retrieval. A storage and retrieval system using computers has been developed to handle the increasing volume.

During the past 10 to 12 years, the practical applications of cryogenic fluids and cryogenic techniques have expanded greatly in both volume and variety. This expansion has led to vigorous engineering research activity on the part of the commercial gas producers, universities, and Government contractors. The increasing cryogenic engineering capacity of non-NBS units is reflected in the changing nature of the CEL program. During its early years CEL's work consisted largely of development of useful engineering applications to fill the needs of the Atomic Energy Commission, the Department of Defense, and, more recently, the National Aeronautics and Space Administration. Currently the program of CEL is being oriented toward more fundamental research, such as the measurement of properties of materials; the study of fluid flow and heat transfer phenomena; and the establishment of standards. The Laboratory was made a part of the Institute for Materials Research at the time of the reorganization of the Bureau in February 1964. CEL continues to provide important engineering service in areas where it has unique capabilities of personnel and equipment.

CEL is functionally organized into seven sections, as follows:

1. *The Cryogenic Properties of Solids Section* is concerned with the measurement, analysis, and correlation of the properties of solids under cryogenic environments. Basic research is conducted to gain a better understanding of the properties. At the present time, about three-fourths of the work is concerned with mechanical and electronic properties of metals. The staff also works with materials and material systems of special technological importance such as polymers, insulations, and cryogenic magnets.

2. *The Cryogenic Properties of Fluids Section* is conducting research on the properties of low-boiling-point fluids used in cryogenic processes, and is studying phase equilibria in single and multi-component systems. The section's continuing program to determine the physical and thermodynamic properties of hydrogen is one example of its contribution of new data for design engineers.

3. *The Cryogenic Data Center Section* facilitates the dissemination of information of cryogenic interest as already described.

4. *The Cryogenic Metrology Section* is responsible for investigation of fundamental principles of cryogenic measurement for industrial, field, and space use. This section was established in 1963 in response to an increasing national need. Its mission is implemented by performing investigations, evaluations, and applications engineering. It performs research on those properties of materials, matter-matter, and matter-energy interactions which may lead to new or improved measurement coefficients. Evaluation programs are conducted to determine calibration sensitivity and dynamic response of commercial transducers. The evaluations aid manufacturers in improving their devices and aid other Government agencies in selection of transducers. Applications engineering is concerned with sampling problems, location, mounting, and configuration of transducers.

5. *The Cryogenic Systems Section* investigates basic problems and phenomena associated wth cryogenic engineering technology to explain and predict the behavior of cryogenic systems. It also furnishes consultation and advisory services to other Government agencies and to the public, and assists in establishment of standards required for cryogenic applications.

6. *The Cryogenic Fluid Transport Process Section* has responsibilities related to basic understanding and applications of heat, momentum, and mass transport of cryogenic fluids; and preparation of cryogenic engineering handbook data. The research effort is planned to provide urgently needed design information. The handbook preparation provides engineers with effective design information and computational aids. The research and handbook operations complement each other as the research program helps keep the handbook work in conformity with recent developments and the handbook effort often reveals needed areas of research.

7. *The Cryogenic Technical Services Section* provides support of the CEL research program. Its activities include engineering design of cryogenic apparatus; fabrication and installation of experimental equipment; centralized stores for supplies and instrumentation; operation of unique process facilities for Bureau research and testing; distribution of liquefied and purified gases; and calibration and maintenance of laboratory instruments.

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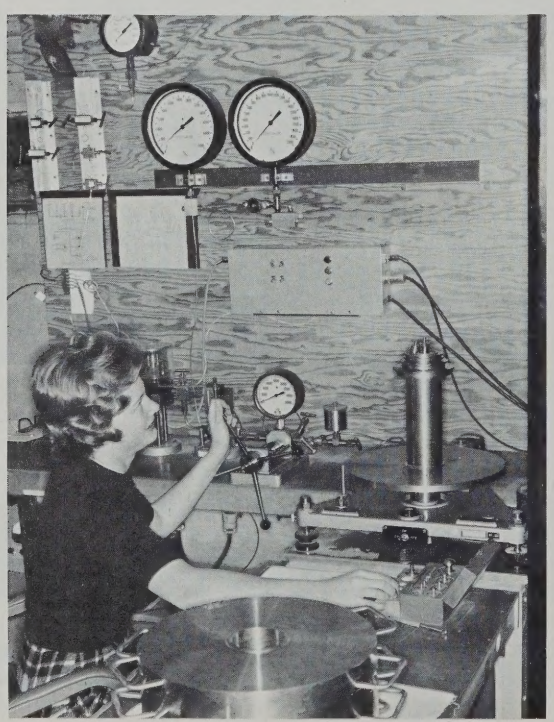
Physical and Thermodynamic Properties of Parahydrogen

THE Cryogenic Engineering Laboratory is conducting precision measurements on the physical properties of fluid parahydrogen at cryogenic temperatures up to 100 °K, and at pressures to 350 atm. Thermodynamic functions have been derived and tabulated for this range of conditions, and transport properties such as viscosity are currently being determined. These data are required for engineering design and performance purposes for the large-scale production and use of liquid hydrogen.

For some years, hydrogen was described as a "permanent gas," meaning that it could not be liquefied. Expansion through an orifice, under ordinary conditions, produces a warming, rather than the desired cooling effect. From its initial liquefaction by Sir James Dewar in 1900, liquid hydrogen remained a subject of academic interest until the first large-scale liquefier, designed for the Atomic Energy Commission by the National Bureau of Standards, was constructed at Boulder. Thereafter, ever greater requirements for liquid hydrogen were presented by the newborn space program.[1] [2] Anticipating the need for physical properties data, the Bureau in 1958 initiated a program of measurements on hydrogen. Principal support for these measurements has come from the Air Force and the National Aeronautics and Space Administration. Theoretical understanding of the fluid state proved to be inadequate to give useful estimates of the required properties, and further theoretical advances depended upon precision measurements for guidance.[3]



The acquisition of these precision measurements, always difficult and expensive at cryogenic temperatures and high pressures, was further complicated by the existence of two molecular modifications, ortho- and parahydrogen. Since these exist together in relative amounts determined, at equilibrium, only by the temperature, it is necessary to perform measurements on a mixture rather than on a single pure substance. These modifications arise from nuclear spin orientations (a subject covered more fully in the compendium of properties prepared by Woolley, Scott, and Brickwedde in 1948).[4] For practical purposes, the equilibrium is established quite slowly in the absence of a catalyst, and the only gross difference in properties occurs in the internal energy and related thermal properties. The heat of conversion, for example, is comparable with the heat of vaporization, such that when ordinary hydrogen (75 percent ortho) is liquefied in the absence of a catalyst, the ensuing spontaneous exothermic conversion to 99+ percent parahydrogen, at the low temperature of the normally boiling liquid, results in nearly total evaporation from a perfectly insulated container.[5] Since equilibrium *liquid* hydrogen is nearly all in the para-modification, advantage has been taken of the slow conversion rate to measure properties of this limiting mixture at absolute temperatures up to five times the boiling point. Conversion rates are important in most engineering problems. Research in this field is in progress elsewhere.[6]

Most useful for engineering applications are tables of the thermodynamic functions (energy, entropy, specific heat). The pressure-density-temperature (P-ρ-T) relation is fundamental. Accurate data yield the density-dependence of thermodynamic properties at constant temperature. Experimental specific heats, on the other hand, yield temperature-dependence of energy and entropy at constant density. Both types of data, used on closed paths of computation, provide a method for testing the self-consistency of a thermodynamic network. Some practical difficulties are encountered.[7] At temperatures below the critical, paths of computation cross the two-phase region, necessitating determination of additional categories of data, namely all of the P-ρ-T properties of the saturated phases, including the poorly definable critical point. The computations involve integrals of $(\partial P/\partial T)_v$ and $(\partial P^2/\partial T^2)_v$, the slopes and curvatures of plots of P versus T at constant density (isochores). These plots, however, are very nearly linear. Accurate curvatures may be derived only if the P-ρ-T data are very closely spaced, and have an accuracy and precision better than 1 part in 10,000. Since the computations involve two independent vari-

A precision dead-weight gage was used to determine accurately the hydrogen fluid pressure in recent *P-V-T* research. Mrs. Jo Ann Harlan's right hand rests on small weights used with the gage. Large weights used to measure high pressures are in the foreground. Measurements are accurate to 1 part in 10,000.

ables, an equation of state is needed for smoothing in two dimensions, for interpolation, and for computational manipulation; yet none exists of the desired extreme accuracy.

The design of experimental equipment for P-ρ-T and specific heat determinations was begun in 1958 by R. D. Goodwin,[8] and measurements were completed in 1961 with coworkers in the Section on Properties of Cryogenic Fluids.[9, 10, 11, 12] Results have been summarized,[13] and they include 1211 P-ρ-T data triplets in the range 15 to 100 °K at pressures from 2 to 350 atm. Experimental or computational results include the vapor pressure/temperature relation; the orthobaric densities; the critical constants; the freezing liquid P-ρ-T relation; the virial coefficients; the specific heats of saturated liquid; the specific heats for a wide range of compressed fluid states; the heats of vaporization; the Joule-Thomson inversion curve in P-ρ-T coordinates; tables of thermodynamic functions, derived specific heats, and derived sonic velocities.

Computational work is in progress on the equation of state, and experimental determinations of the transport properties are partially completed. These measurements, again, are being conducted under the extreme conditions of cryogenic temperatures and high pressures. They include viscosity, thermal conductivity, and sonic velocity. Dielectric constants have been calculated [14] and measured [15] over the above wide range of conditions.

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[14] *Robert J. Corruccini,* Dielectric constant of liquid parahydrogen, *NBS Tech. Note 144 (PB 161645) (Apr. 1962).*

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New Book on Low Temperatures

A NEW BOOK, *Cryogenics* (Reinhold Publ. Corp., New York), has been written by Michael McClintock, a staff member of the NBS Boulder (Colo.) Laboratories. The book is an easy-to-read introduction to the cryogenic field for engineers, scientists, and nonscientists. It is designed to give a qualitative understanding of the basic aspects and applications of cryogenics to readers unfamiliar with the low-temperature field. However, as stated in the foreword by R. B. Scott, Manager of the NBS Boulder Laboratories, the book should also be enjoyable and useful to scientists and engineers engaged in cryogenics.

The first chapters cover production, maintenance, and measurement of low temperatures. Later chapters contain explanations of unusual behaviors of liquids and solids at low temperatures. The last chapter is devoted to representative applications of cryogenics.

With the increased interest in cryogenics today, this book is timely and should be useful to anyone wanting to know about work in the low-temperature field.

RADIO STANDARDS

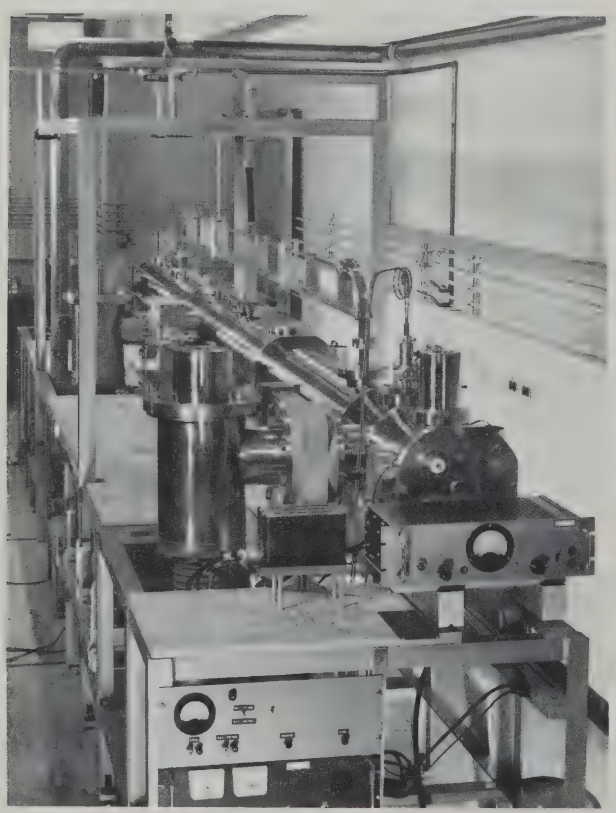
1954–1964

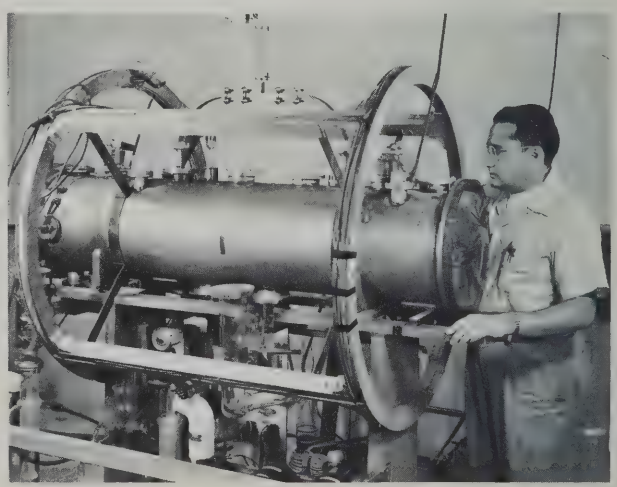
NBS WORK in radio standards began in 1911 with a frequency calibration made by J. Howard Dellinger. It was, as Dr. Dellinger said later, ". . . just a small offshoot of a number of electrical tasks one member of the Electrical Division was doing. . . ." By 1946 this effort had grown from one individual in the Electricity Division to two sections in the Central Radio Propagation Laboratory. With the move to Boulder in 1954 these two sections became the Radio Standards Division with an initial staff of about 50 people.

This modest beginning formed a strong nucleus for the work to follow. NBS had exhibited the world's first atomic clock in 1949. By 1950 the staff had developed the micropotentiometer for the measurement of small rf voltages up to 300 MHz. Also, by 1950 frequency calibrations extended to 30,000 MHz and other calibration services existed on a very limited scale. Development was under way in the areas of power, impedance, voltage, attenuation, field strength, noise, and the electromagnetic properties of materials.

Since 1954, NBS areas of research and development in radio standards have expanded to reflect both the work of the early 50's and also the newer needs of the electronics industry. Today the Radio Standards Laboratory is a leader in the development of frequency standards and their dissemination; it has excellent facilities for the measurement of both rf and microwave power; it has strong facilities in the other dominant areas of electromagnetic measurement; and its slender calibration efforts of the early 50's have grown into the Electronic Calibration Center which annually calibrates thousands of standards over a frequency range from zero to nearly 100 GHz.

The Laboratory also is heavily involved in studies using quantum physics as a basis for new radio standards; it has developed competence in the millimeter region and in plasma physics; it is a leader in the international comparison of radio standards; it is helping to train others in the newest techniques by offering workshops and courses in electromagnetic measurements; and it maintains close contact with both research and industry—with a particular desire to pinpoint and meet the needs of industry.





Left: **A new cesium-beam frequency standard (NBS III), 18 feet long, is now being evaluated. Its length (about 8 feet longer than earlier models) should significantly increase the precision, since the spectral line width is about 45 Hz as compared with 110 Hz in the previous model. The new model can also be used with thallium.** *Below:* **Henry Salazar is shown adjusting the experimental cesium-beam frequency standard shortly after it was moved from Washington to Boulder in 1954. With modifications, both internal and external, including removal of the open cylindrical frame (Helmholtz coils), the instrument is now the NBS I atomic frequency standard. With two additional standards in operation, NBS I has been further modified for research with thallium.**

Early this summer the Electronic Calibration Center (ECC) completed its 20,000th calibration. The first, measurement of a high-frequency *Q* meter, was reported to the Navy on February 14, 1958. In these 6½ years, the program of the ECC has been greatly enlarged, the number of services increased, and the range of calibrations extended, both as to frequencies and as to the magnitude of the quantity being measured. A significant trend has occurred within the past year in the nature of the workload. Previously, the workload for the Department of Defense was approximately 50 percent greater than that for the public, but during the year the two have become about equal, with a continuing rise in calibrations being made for the public.

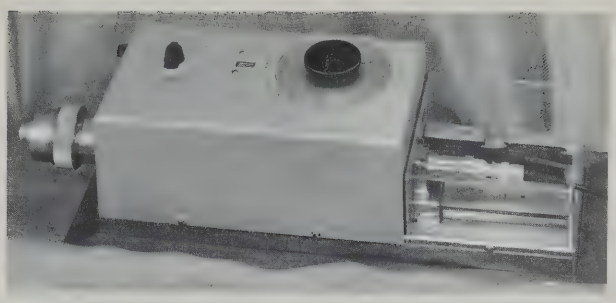
Frequency Standards

The most striking developments over the past decade have been in the area of frequency standards and their distribution. In 1957 cesium and ammonia beam spectrometers were operated for the first time in Boulder. Their precisions were 1 part in 10^9. In 1958 a second cesium beam apparatus was built and the original model was completely rebuilt. A comparison between the two was made over several months in 1959 and their frequencies agreed to an accuracy of about 1.5 parts in 10^{11} with a precision over several hours of 2 parts in 10^{12}. On January 1, 1960, the newest cesium beam became the device which provides the U.S. Frequency Standard (USFS).

Since 1960 the accuracy of the cesium beam standard has been refined to 1 part in 10^{11} and this is expected to be further improved by a new cesium beam which is about three meters long. There have also been interesting developments with thallium as an alternate frequency standard, and work is progressing on the development of a hydrogen maser.

Developments with atomic frequency standards raised the question of whether or not an atomic time scale could be maintained. Thus RSL began the development of an atomic time scale, capable of being synchronized or related to clocks at any remote location, and powered by an unfailing frequency source referenced to the U.S. Frequency Standard. Such a time scale was established in 1961. Later, by using a quartz-oscillator clock as a portable comparator, the scale was related to the time pulses of WWV, to the atomic time maintained by the Naval Observatory, to the time pulses of the Loran-C master station at Cape Fear, N.C., and to clocks at other laboratories.

The progress in the atomic measurement of time at NBS and other laboratories has led to consideration by the General Conference on Weights and Measures of defining the second in atomic instead of astronomical terms. It is probable that international agreement on the use of atomic standards for high-accuracy work will be reached this October in Paris.



Waveguide-below-cutoff attenuators serve as working standards in many of the measurement systems used in the Electronic Calibration Center.

As the atomic standards were refined, similar progress was made in the dissemination of the U.S. Frequency Standard. In 1954 the USFS was disseminated only via shortwave broadcast by WWV, near Washington, D.C., and by WWVH in Hawaii. Two years later the Laboratory began experimental transmissions at 60 kHz over WWVB in Boulder. This station radiated only 1½ W, but it proved that the lower frequency did offer much higher accuracy for those laboratories which could receive it.

Success with the 60-kHz transmission led to an experimental 20-kHz transmission in 1960 (theoretical studies had indicated that 60 kHz would be more stable over the continental United States but that 20 kHz offered greater stability for global transmission). The 20 kHz station, WWVL, radiated only 15 W, yet it was promptly picked up as far away as New Zealand. These experiments led to the construction in 1963 of more powerful transmitters and more efficient antennas at Fort Collins, Colo., for both WWVB and WWVL. WWVB now has a radiated power of about 2 kW and WWVL—still on an experimental basis—has a radiated power of about 500 W. The carrier signal of each station is phase locked to an atomically related time scale. This phase control of the low-frequency transmission means that clocks at remote locations, once synchronized, can maintain—to within a few microseconds—the accuracy of the U.S. Frequency Standard.

Radio Frequency Standards

For about four years after the move to Boulder major efforts in the areas of radio frequency and microwave standards were devoted to the development, construction, and installation of equipment in the Electronic Calibration Center. There had never been such a center before, and during these first few years several million dollars and about 50 percent of the staff's time were spent in equipping the center.

There were, however, many valuable developments in research. By 1956 a new AT (attenuator thermoelement) voltmeter demonstrated an improvement of more than an order of magnitude in both absolute accuracy and in calibration stability over the conventional vacuum-tube voltmeter. It also extended the range in both frequency and voltage.

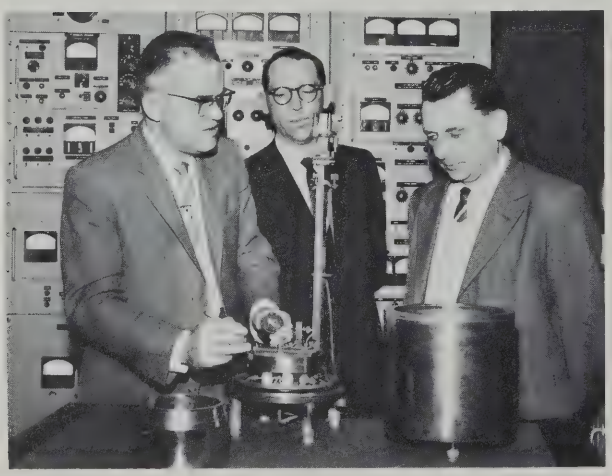
In the field of impedance, a dramatic development was the achievement of a high-precision connector. Rather than having male or female elements, the terminals of this connector have flat faces, perpendicular to the axis, which allow the highest accuracy of the primary standard while giving the least loss of accuracy in transfer to calibrated instruments. This development made it possible to improve impedance measurements by about two orders of magnitude. At the same time it became possible to intercompare capacitors, inductors, and resistors (and therefore attenuators, power meters, and voltmeters) on the same mounts to detect possible calibration errors. This connector is now beginning to be used in industry and in other quantities of radio measurement.

By 1958 there existed a set of national primary power standards for use up to 300 MHz. These included the 0- to 100-mW thermistor bridge, the 1-mW to 10-W bolometer bridge, and the 200-mW to 20-W dry static calorimeter. The overall accuracy of 0.5 percent provided a marked improvement over previous accuracies and ranges.

A new development in the field of pulse radio frequency power—which formed the basis for a new calibration service—occurred in 1961. In this new method the power level of a selected portion of the pulse is compared with a known amount of CW power at approximately the same frequency.

At about this time the staff completed an international comparison of rf power (300 MHz) with Great Britain and later with Japan (400 MHz)—in both cases agreement was within the limits of experimental error. Thus for the first time it was known that the rf power measurements of all three countries are in close agreement.

The basis for a new calibration service has been provided during the past year by a noise power comparator which measures noise power from 10^{-18} to 10^{-21} W with a precision of at least 1 percent. This improvement in sensitivity and precision is achieved through the use of a two-channel radiometer developed by the staff. With refinements the comparator is expected eventually to achieve a precision of at least 0.02 percent.



View from top of one of the 400-ft towers which support antennas

Now nearing completion is an improved standard for calibrating rf attenuators which promises to provide an accuracy of 0.0001 dB per 10 dB in the near future. This standard is a self-calibrating, high-sensitivity insertion-ratio measuring system. It also has the ability to provide both the insertion phase angle and the insertion loss.

Microwave Standards

In 1954 only the attenuation and frequency standards were sufficiently advanced to justify the offering of a true calibration service in microwave measurements, although much valuable pioneering work had been done in the fields of microwave power, noise, attenuation, impedance, and frequency.

Within four years after the move, however, remarkable improvements in the accuracy of microwave power measurements had been achieved through the development of a self-balancing d-c bolometer bridge, a highly stable signal source, and the careful analysis and refinement of the NBS microcalorimeter. The 0.2 percent accuracy of these measurements raised NBS to world leadership in the field.

These developments also made possible the first international comparisons of microwave standards of any kind and, in 1957 and 1958, microwave power comparisons were made with Japan and the United Kingdom. All comparisons were within the limits of ex-

Construction details of the NBS microcalorimeter—the U.S. standard of microwave power—are explained to Dr. Wolfdietrich H. Schaffeld (*right*), head of the Microwave Physics Laboratory, Physikalisch Technische Bundesanstalt, Braunschweig, Germany. *Left to right:* Glenn Engen, Dr. George Schafer, and Dr. Schaffeld.

of the new 60- and 20-kHz transmitting stations at Fort Collins, Colo.

perimental error and, at 10 GHz, agreement was within 1.5 percent.

Microwave impedance standards and measurement techniques were brought to a high state of accuracy by 1959, when the tuned reflectometer was fully developed at NBS, and when both half-round inductive obstacles and quarter-wavelength short-circuit impedance standards were carefully evaluated. For the first time, impedance standards were available in which a high degree of confidence existed.

The following year two methods of measuring attenuation were reported—each capable of accuracies from within 0.0001 to within 0.06 dB over a range from 0.01 to 60 dB. One method employs differential power measurements by refined bolometric techniques, and the other is a modulated subcarrier system which lends itself to audio frequency techniques. In 1960 accuracies of these techniques exceeded the precision to which available attenuators could then be set and read.

A concerted effort on the development of microwave noise standards resulted, in 1962, in the establishment of a calibration service for WR 90 waveguide (8 to 12 GHz) standard noise sources. This was based on a hot load operating at approximately 1,000 °C and a thoroughly evaluated, sensitive radiometer for noise standard comparisons.

Work on microwave phase shift standards began in 1958, and the tunable reflectometer developed for impedance measurements was applied as a standard phase shifter. A modulated subcarrier technique was also developed as a sensitive method of measuring microwave phase shift. The basic theory of phase-shift measurements and standards has been developed by NBS during the past few years.

Present work in this area is concentrated on the development of microwave standards of field strength and high power where there are no existing NBS calibration services.

Extremely High Frequencies

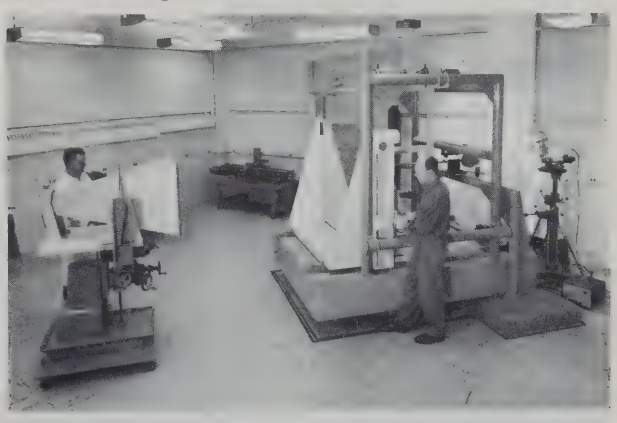
As early as 1952 NBS began conducting research at frequencies ranging from the shorter microwaves to millimeter waves to develop methods of generating, transmitting, and detecting energy in this region, and to explore applications of these frequencies to the measurement of significant physical quantities.

By 1956 a pilot-model microwave interferometer of the Michelson split-beam type had been built and operated at 6 mm as a first step in its development for measuring the velocity of light. The final version (which has a 2-ft sq horn and a 5-ft sq aluminum mirror) was in operation by 1962. The measurement has been delayed by diffraction effects that have required extensive mathematical analysis, but encouraging initial measurements reveal a standard deviation of a single measurement of about 0.2 to 0.3 km/sec. It is expected that this can be improved significantly for the final measurements.

A major achievement of the past ten years was the development of the Fabry-Perot interferometer designed to operate at millimeter wavelengths. The initial design of this interferometer began about 1957; by 1961 the instrument had been used to measure the length of millimeter waves to accuracies of better than 0.04 percent. In experiments with waves about 6 mm long, the resonant cavity attained Q values of around 100,000. The interferometer has been used to measure dielectric constants and loss tangents of materials in sheet form, and to make refractive index measurements on a variety of common gases to an accuracy of ± 1 part in 10^7.

The completely new type of resonator provided by the Fabry-Perot interferometer is now being applied in refractometers and spectrometers. During 1962 an absorption cell was built which uses a parallel-plate interferometer for the observation of Stark effects in molecular spectra. The Stark effect concerns the splitting of

Final tests are being conducted on the Michelson interferometer prior to measuring the speed of light at millimeter wavelengths.



spectral lines by the application of electric fields, and provides an unexploited possibility of measuring d-c and low-frequency voltages to high precision. The device has been tested at voltages up to 5000 V and has achieved short-term precisions of 1 or 2 parts in 10,000. It is now being refined with the expectation that the precision will be improved by one or two orders of magnitude.

Another application uses a miniature (2-in.) spherical-mirror Fabry-Perot resonator in a series of wavemeters covering the frequency range from 50 to 140 GHz. Experimental evaluation during the past year has shown that these have Q values many times that of commercial wavemeters and are easily read to three significant figures with no individual calibration curves required.

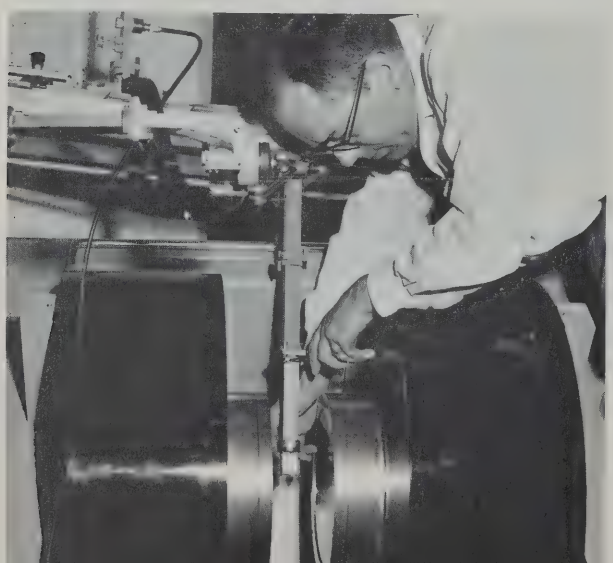
One of the newest programs in microwave physics is the development of an extremely wide-band absolute power standard based upon the pressure exerted by electromagnetic radiation on a perfect reflector. The standard is expected to cover the frequency range from 1 mm to visible light—10 octaves of the electromagnetic spectrum—in a single instrument.

Materials

A study which extended over much of the past ten years was a materials analysis program for the Bureau of Ships. Measurements were made on the magnetic characteristics, and on those parameters important to understanding material properties, of ferrimagnetic materials used in the radio and electronics industry. Tensor permeability studies, which were a part of this program, became possible when the staff developed an exact solution to a bimodal cavity which permitted the exact analysis of tensor permeability.

In 1958 the Department of Defense asked the Laboratory to establish facilities for the large-scale evaluation of materials, and for the complete investigation of certain classes of materials. These facilities now offer the unified program necessary for meaningful correlation and referencing of the electromagnetic constants of selected materials in the rf and microwave spectra.

Lawrence M. Matarrese places a waveguide cavity, containing a crystal specimen, between the poles of a magnet in studies of magnetic resonance. The objective is the establishment of standards and measurement techniques, based on a better understanding of the interaction of electromagnetic waves with matter.



Along with these developments there have been continuing advances in primary standards and basic research in both the magnetics and dielectrics areas. During the later 50's these studies led to continual improvements in specific instruments such as those used to study the magnetic and dielectric spectra of radio materials. By 1960 a permittimeter had been developed which makes it possible to measure complex rf permittivity or conductivity up to about 50 MHz without applying electrodes to the material. A microwave conductivity service was instituted as well.

During the early 60's a theoretical study of the complex tensor permeability led to a basic investigation of ferrimagnetic resonance (FMR)—especially of losses which may be related to spin waves. Two new and important methods were recently developed for studying the FMR loss versus coupling to the spin-wave spectrum.

Also during the early 60's the Laboratory began magnetic resonance studies to determine energy levels, crystalline fields, relaxation times, and transition probabilities in paramagnetic and antiferromagnetic crystals. An electron paramagnetic resonance spectrometer was built and is being used for the observation of interesting electron paramagnetic resonance spectra in materials such as iron-doped quartz, calcite containing manganese ions, amethyst and topaz, and a program to provide controlled specimens such as doped single crystals was also introduced.

Recently research has begun on antiferromagnetic resonance and the interaction of phonons and spins. Sizable single crystals of antiferromagnetic copper sulfate were produced and are being investigated. The phonon-spin interaction is studied using nuclear magnetic resonance as a diagnostic tool.

Radio Plasmas

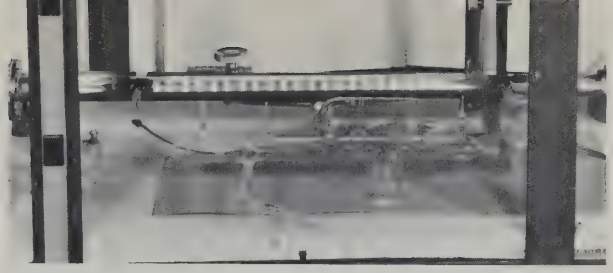
Since the interaction of radio waves and plasmas is a subject of much theoretical and practical interest, NBS began a study of radio plasmas in 1959. The goal is to develop precise measurement techniques and basic data on the fundamental properties of ionized gases.

A major initial project was the radio probing of a dense, highly magnetized, and bounded plasma by using the British thermonuclear machine ZETA. The early theory for this experiment indicated the possibility of accurate determination of the internal magnetic field, electron density, and electron temperature of extremely dense plasmas. Analysis of the ZETA data, however, revealed additional effects not explained by the early theory. A detailed solution for bounded plasmas has since been developed and is presently being checked.

During the past few years attention has been paid to the development of diagnostic methods based on microwave techniques and optical spectroscopy as well as to the development of stable and uniform plasmas.

Quantum Electronics

Since 1960 the Laboratory has become increasingly involved in research studies applying quantum physics to radio standards. The atomic frequency standards, the use of the Stark effect as a voltage standard, and the



Research on precise measurement techniques and basic data on the fundamental properties of radio plasmas is conducted at the Radio Standards Laboratory. Almost all laboratory plasmas (horizontal cylindrical tube, *center*) are nonuniform and exhibit structures as illustrated above. Such structures, caused by nonlinear flow mechanisms, must be better understood before they can be used effectively.

investigations of magnetic resonance have been mentioned. Other research in progress in this area includes the measurement of the velocity of gamma rays by means of the Mössbauer effect, the measurement of the fine-structure constant by determining the fine-structure separation in singly ionized helium, and a study of the various mechanisms of inducing blue fluorescence in anthracene with the red light of a "giant pulsed" ruby laser. In addition a small but significant research effort in optical laser phenomena has been established, which will serve as the basis of a possible future standards program for selected laser properties.

Theoretical Physics

A project which has been continuing for several years has been the preparation of a set of microwave spectral tables which are being published in five volumes. By providing an up-to-date catalog of information these tables will aid researchers in the identification and analysis of microwave spectra, with significant application to industrial chemical analysis and control.

During the late 50's, to meet the needs encountered in the microwave measurement of the velocity of light, the staff developed a general theory of diffraction in reflection and transmission systems. This provided an analytical tool for the original problems and also led to further theoretical work. One recent result permits electromagnetic field measurements with arbitrary probes.

About 1960 new perturbation formulas were developed and used to obtain approximate results in a variety of waveguide junctions. The formulas were applied in particular to make finite conductivity calculations for new impedance standards consisting of half-round obstacles in rectangular waveguide.

In 1962 a significant paper was presented which described some generalized variational principles for electromagnetic vibrations and applied these principles to the theory of waveguide junctions. During the same year calculations were completed on the bound state energies of an exponentially shielded Coulomb potential, that is, the Debye-Hückel potential in ionized gases. Recently a quantum statistical mechanical theory has been developed which may be the first fundamental and successful calculation of properties of a plasma model more realistic than the familiar electron-gas model; the expansions are carried to a higher order than they have been heretofore, and corrected lower-order terms are obtained.

Other Developments

The advances in the technical areas have been coupled with advances in the areas of administration, education, and communication. In 1962 the Radio Standards Division was reorganized as the Radio Standards Laboratory consisting of two technical divisions and a Laboratory office. This has provided the basis for expansion tailored to the needs of the electronics industry. A guideline for such expansion is being provided by a long-range planning committee which annually compares the present Laboratory capabilities with the needs of industry and—in view of these—outlines the program for the next five years. Provision of the physical facilities for expansion began in 1963 with the initial design of a new multi-million dollar building for the Radio Standards Laboratory. This design is now almost completed.

Contact with both industry and research is closely maintained through a series of measurement research conferences held in conjunction with the Aerospace Industries Association, through national conferences sponsored and hosted by the Laboratory, and through selected speakers who are invited to present lectures describing their measurement needs or new developments in their field. The biennial Conference on Precision Electromagnetic Measurements, which began in 1958, is now firmly established as a significant forum for the interchange of ideas. Although it is a national conference it has developed good international participation. This Conference has also led to the birth of the National Conference of Standards Laboratories and to a special committee representing both NBS and industry which has reduced the uncertainties of high-precision connectors by an order of magnitude.

There has been increasing contact with foreign laboratories. During the past year there was an exchange of U.S. and Soviet metrology delegations, and the Laboratory has since received a Soviet proposal for extensive high-frequency and microwave comparisons. Three European countries have expressed a desire to duplicate the NBS microwave power-measuring equipment.

The Laboratory has begun a strong education program for both industrial and research personnel by providing a microwave workshop in 1962 and a three-week course in electromagnetic measurement in 1963. Also, the publication rate of the Laboratory during the past few years has risen to a little more than one professional paper per week.

Since 1954 the size of the Laboratory staff has expanded from 50 to more than 300 people, the technical program has experienced a similar growth, and, in some respects, the present Laboratory facilities are the best in the world. Yet studies reveal a requirement for strong continued expansion if the Laboratory is to meet the real and expressed needs of the swiftly growing electronic industry. It is expected, therefore, that the next ten years will be a period of even more dramatic growth.

High-Q Microwave Cavities

CONTINUING study in the field of microwave physics at the NBS Radio Standards Laboratory has led to the development of resonance cavities having high values of Q (figure of merit) for selected frequencies. Alan R. Cook, Lawrence M. Matarrese, and Joseph S. Wells, of the Radio and Microwave Materials Section, with the assistance of instrument makers in the Instrument Shop, have devised a technique for fabricating thin-walled cavities having either continuous or wound walls.[1]

A cavity whose walls are thin as compared to skin depth of the modulation frequency results in less attenuation of the modulation amplitude than one whose walls are of comparable or greater thickness than the skin depth. The cavities which are fabricated by the new technique possess the thin-wall feature. The wound wall, in addition, permits curbing resonance in modes competing with the desired one.

The upward expansion in use of the radio spectrum has created a continuing need for new circuits and components suitable for higher frequencies. Contributions to the state of the art both at the Bureau and at other laboratories have included developmental work on cavities resonant at microwave frequencies, notably cavities having thin metal walls deposited on materials transparent to radio energy. Glass and ceramic materials have been tried for this purpose; such cavities have been found to have improved electrical characteristics, but poor mechanical properties.

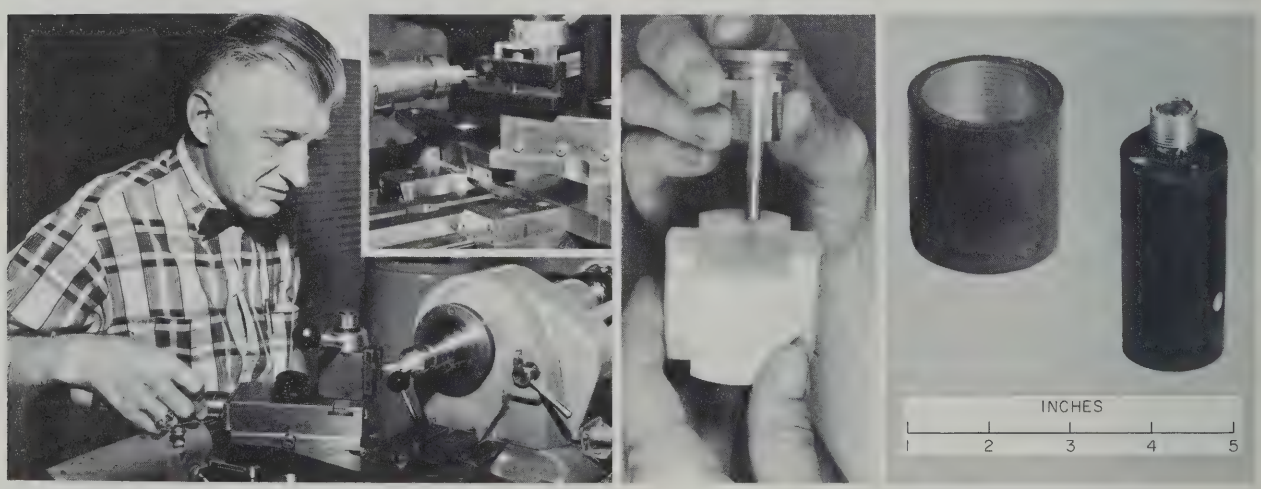
One problem encountered is that a cavity can resonate in several different modes simultaneously, whereas operation is desired in only one mode at a time. In some cases cavity operation in the desired mode of resonance geometry is found to be degenerate, resulting in a low Q for the cavity. A solution to this problem requires a cavity that can be controlled so that the desired mode predominates.

Thin-Walled Microwave Cavity

In this study Cook, Matarrese, and Wells sought a solution by using the fact that the desired family of modes (TE_{01n}) has only annular components of wall current in a cylindrical cavity, whereas other modes have longitudinal components also. Cavities improving performance in a desired mode (TE_{011}) by discriminating against all others (increasing resistance to longitudinal paths) had already been made, using wire-wound walls. An accurate and uncomplicated way of fabricating such cavities has now been devised.

The new cavities which they have made obtain the advantages of the thin-walled and wound-wall cavities by simple fabrication means. The wall is formed by electrodepositing silver to a thickness of 0.010 in. on an aluminum mandrel, previously machined to the desired inside dimension of the cavity. The silver surface is then treated with pumice, the mandrel positioned in a mold, and the space between filled with evacuated epoxy casting compound. After the epoxy has cured, the mold is removed. The aluminum mandrel is then dissolved in a bath of concentrated sodium hydroxide, leaving the silver and epoxy unaffected. The hardened epoxy physically supports the silver, which forms the actual radio frequency cavity.

The silver film can be obtained as a precisely wound wall by machining a spiral groove barely through the silver coating on the mandrel, before potting. The result is a cavity with characteristics similar to those of



High-Q microwave cavities have been made by a new technique in which a thin layer of silver is plated on an aluminum mandrel machined to the desired inside diameter of the cavity. The silver is then slotted on a lathe to make a continuous spiral which will form the wall of the cavity (*left*). The aluminum mandrel bearing the slotted wall is positioned in a mold to be cast in epoxy (*right center*). Finally, the aluminium is dissolved in concentrated sodium hydroxide, leaving only the silver walls, epoxy, and encapsulated coil (*right*).

the previously produced wire-wound cavities and having other advantages besides. A modulating coil can be suspended in the mold and potted within the cavity-supporting wall. The easy machinability of the epoxy facilitates attaching the cavity to the waveguide. These cavities are resistant to breakage and have even been subjected to liquid-helium temperatures with little adverse effects.

Cavities fabricated by the plating-potting-dissolution method have been successfully used in the laboratory for an extended period of time. Unloaded Q's of 15,000 for a grooved X-band cavity and of 10,000 for a K-band cavity have been obtained. One continuous-wall version of a K-band cavity was found to have an unloaded Q close to the maximum theoretical value of 18,000.

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[1] A new method for constructing epr cavities, *by A. R. Cook, L. M. Matarrese, and J. S. Wells, Rev. Sci. Instr.* **35,** *114–115 (Jan. 1964).*

1964 Conference on Precision Electromagnetic Measurements

MORE THAN 600 conferees attended the 1964 Conference on Precision Electromagnetic Measurements (CPEM), held at the Boulder Laboratories June 23–26. This fourth biennial conference was jointly sponsored by the NBS Radio Standards Laboratory, the Group on Instrumentation and Measurements (PGIM) of the Institute of Electrical and Electronics Engineers, and U.S. Commission 1, Radio Measurement Methods and Standards, of the International Scientific Radio Union. It was also supported in part by the National Science Foundation.

The 1964 CPEM opened on a note of optimism when John M. Richardson, host representative and Chief of the Radio Standards Laboratory, announced that the sponsors had subscribed to a Conference charter which provides formally for the continuation of the series. This note was augmented by an evaluation of the CPEM by Edward W. Houghton of Bell Telephone Laboratories, Inc., keynote speaker and Chairman of the General Arrangements Committee, who called the CPEM "a national resource" when he pointed out that the CPEM "reports the finest techniques and best ideas for precision measurements that have been developed throughout the nation and the world. . . . Invariably many of the ideas and techniques revealed in papers selected . . . have come into general usage in a short time. Thus the ability of the CPEM to identify and highlight significant new measurement developments which will become a part of the expanding capability of science and technology can be properly regarded as a national resource." Dr. Donald Schon, Director of the NBS Institute for Applied Technology, sounded another encouraging note when he indirectly praised the electronics industry for its willingess to accept innovation—thus leading ". . . civilian industry in investment and research and the use of research results."

Forty-seven papers, approximately one-third of those submitted to the Technical Program Committee, were given in the eight sessions of the Conference. The eight sessions covered five general areas: Frequency and Time Standards and Techniques, Quantum Electronics, Direct Current and Audio Frequency Measurements, Radio Frequency and Microwave Measurements, and Measurements on Materials.

The international aspect of the Conference was emphasized by the facts that 10 papers were presented by foreign scientists, that the 29-man Honorary Committee contained the names of 8 foreign members representing as many countries, and that many foreign scientists who did not present papers were in attendance.

The program also provided a broad cross section of important research on precision electromagnetic measurements in the United States. Thirteen industrial or private laboratories and research agencies, the three military services, five universities and institutes, and the Bureau were represented.

Most of the papers presented at the 1964 CPEM will be submitted for publication in the Transactions of the IEEE Instrumentation and Measurements Group. They will appear in a single issue of the Transactions which has a tentative publication date of December 1964.

The next CPEM is scheduled for June 21–23, 1966.

CHANGES IN NBS RADIO BROADCASTS

Time Signal Phase Adjustment Effective September 1

The time signals broadcast by WWV, Greenbelt, Md.; WWVH, Maui, Hawaii; and WWVB, Fort Collins, Colo., were retarded 100 milliseconds at 0000 UT, 1 September 1964. This joint action of NBS and the U.S. Naval Observatory was taken to synchronize the time signals with sidereal time. The last previous adjustment was made 1 April 1964.

RADIO PROPAGATION RESEARCH

The CRPL Program

THE CENTRAL Radio Propagation Laboratory has the main responsibility within the U.S. Government for collecting, analyzing, and disseminating information on the propagation of radio waves at all frequencies along the surface of the earth, through the atmosphere, and in space. To carry out this responsibility, the Laboratory conducts research on the nature of radio waves and the media through which they are transmitted, the interaction of the waves with the media, and the nature of radio noise and interference effects. A network of field stations is operated from the Arctic to the tropics and the Antarctic, and data are exchanged with other laboratories throughout the world.

Because radio waves and radio communications do not recognize natural barriers or dividing lines between countries, radio research must of necessity be worldwide in scope. Further, the portions of the earth's atmosphere through which radio waves travel vary in behavior with time of day, season of the year, and location on the earth's surface. Therefore, much of the CRPL program is international, both in the origin of data and in the cooperation received from scientific groups of other countries.

International Year of the Quiet Sun

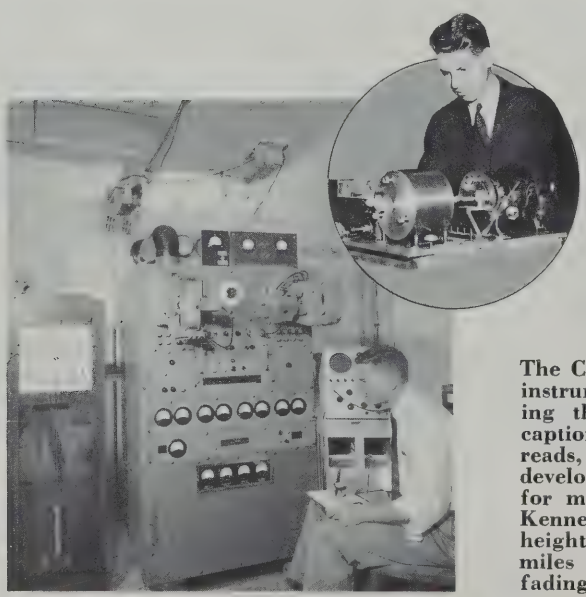
An important international program now in progress is the International Year of the Quiet Sun (IQSY). This program will continue through 1964 and 1965, a period chosen because it is at the minimum of the sunspot cycle when solar disturbances are likely to produce the least interference to radio.[1] CRPL's contributions to this program include coordination and direction of the ionosphere and airglow projects, operation of the Western Hemisphere Radio Warning Service, and operation of the World Data Center-A for Airglow and Ionosphere.

Details of the IQSY programs call for special observations on certain *days* and special treatment of the data obtained. The rapid communications necessary during the "World Days" program are obtained by channeling messages principally through Regional Warning Centers (RWCs). The Bureau's North Atlantic Radio Warning Service at Fort Belvoir, Va., serves as the Western Hemisphere RWC and as the World Warning Agency responsible for declaring Alerts—days of special geophysical interest. CRPL has prepared the Manual for the "World Days" program and the International Geophysical Calendars for IQSY.

IQSY is an extension of two earlier programs, the International Geophysical Year (July 1, 1957 to Dec. 31, 1958) and International Geophysical Cooperation (since Jan. 1, 1959), in both of which CRPL has participated extensively.

Ionospheric Research

One of the main areas of CRPL activity is research regarding the ionosphere, that portion of the earth's atmosphere lying approximately 80 to 800 km above the earth's surface. The Bureau has been active in this field since Appleton and Barnett in England demonstrated the ionospheric reflection of radio waves in 1924, and Breit and Tuve of the Carnegie Institution of Washington introduced pulse techniques to measure ionospheric heights in 1925. As early as 1931, "an interesting new apparatus developed by the Bureau of Standards for making a continuous record of the height of the Kennelly-Heaviside layer (ionosphere)" was reported. This was the first ionosonde, which has been refined and improved through the years to the present model C–4. The C–4 was introduced about 1955, in time for installation at many of the stations making



The C-4 Ionosphere Recorder is the latest model of an instrument developed and improved by NBS for sounding the ionosphere. Dale Reed records data. The caption for the apparatus in the inset, written in 1931, reads, "An interesting new apparatus has recently been developed by the Bureau of Standards at Washington for making a continuous record of the height of the Kennelly-Heaviside layer (ionosphere). Changes in the height of this layer, located approximately 60 to 200 miles above the earth, are closely connected with the fading of radio programs."

The antenna at the Jicamarca Observatory, on the magnetic equator near Lima, Peru, covers an area of 89,000 m² and consists of 9,216 crossed-dipole elements. It is utilized in a method, known as scatter radar, for studying the ionosphere and exosphere.

ionospheric observations as part of the IGY program. The annual rate of ionospheric soundings during IGY was 5 million at NBS-associated stations, 15 million throughout the world.

With ground-based instruments, observations of the ionosphere were, to a great extent, limited to the underside of this region. However, a joint U.S.-Canadian project to investigate the topside of the ionosphere resulted in the S–27 satellite, *Alouette*, being launched into orbit in 1962. Another satellite, NASA's S–48 *TOPSI*, is scheduled for orbit and will furnish complementary data on the irregularities of the top layers of the ionosphere.* Simulaneous observations from above and below have provided CRPL with valuable knowledge about the ionosphere, especially as concerns its thickness, temperature, and constituents.

Transmissions from other satellites have also provided valuable information about the ionosphere. Beginning with the first manmade satellite, Sputnik Alpha, launched by the Soviets in 1957, CRPL has observed and recorded data from many satellites which were transmitting on frequencies that would be useful in ionospheric research.

A new method for studying the ionosphere and exosphere (the portion of the upper atmosphere extending beyond the ionosphere, to its boundary with the interplanetary medium) is based on an extremely weak incoherent scattering of radio waves which is proportional to the electron density. In this method, a powerful beam of VHF radio waves is directed toward the ionosphere. When the radio waves strike free electrons in the ionosphere and beyond, a small amount of energy is re-radiated or scattered back, and can be picked up by a suitable receiver. Known as scatter radar, the method, using ground-based equipment, offers a practical means of measuring electron densities and other atmospheric variables out to a distance of several thousand kilometers.

This work is being done at the Jicamarca Observatory on the geomagnetic equator near Lima, Peru. The equipment comprises a 6-MW peak-power pulse transmitter and an 89,000-m² broadside antenna, containing 9,216 crossed-dipole elements, which are placed 1.8 m above a reflecting groundscreen. The antenna transmits a radio wave lasting between 50 and 1500 μsec and then, switching to the receiving state, detects the faint re-radiation from free electrons in the upper atmosphere.

Radio Noise

Atmospheric radio noise, produced largely by thunderstorms, causes serious interference to radio communications. CRPL has studied this problem as part of the IGY and IGC program. However, well before IGY, CRPL engineers had designed a noise recorder—in effect a sensitive radio receiver—and a number of these were installed in various places on the earth's surface. Numerical maps of radio noise have been prepared, for each season of the year, and for six local time blocks, which can be used to compute the noise level at the receiver.

Prediction Service

A tangible result of the ionosphere research work is the monthly periodical, *Central Radio Propagation Laboratory Ionospheric Predictions*,[2] from which a prediction of the best skywave frequencies over any transmission path, at any time of day, for average conditions for the month, may be determined. The *Predictions* are issued three months in advance and modified as conditions that might affect the prediction change. A report of ionospheric conditions is broadcast over NBS standard frequency broadcast station WWV twice each hour. For almost 20 years the charts were prepared

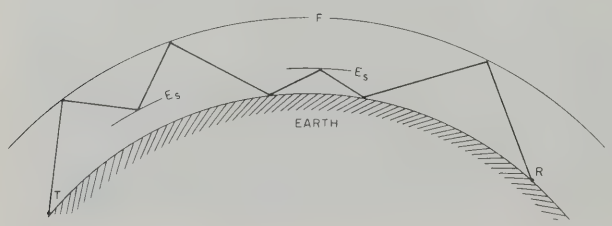
**On August 25, later this issue had gone to press, NASA successfully launched a topside sounder satellite, Ionosphere Explorer A, instrumented for experiments proposed by CRPL. Further details will appear in the October issue.*

A worldwide network of atmospheric radio noise recording stations is centered at CRPL in Boulder. Equipment designed and built according to CRPL specifications is installed at each location. Note the distribution by hemispheres and continents. *Left:* **The station at Boulder.**

by manual and graphical methods, but they are now prepared by electronic computer, using a numerical mapping procedure devised by members of the CRPL staff.

The prediction service dates back 25 years to a report entitled "Characteristics of the Ionosphere at Washington, D.C." by Gilliland, Kirby, and Smith of the NBS staff and published in the March 1939 issue of the *IRE Proceedings.* Following is an excerpt from their paper: "This report inaugurates a new service, the forecasting of radio transmission data for the month following the one in which this report is published. The illustration gives the expected monthly average values of the maximum monthly usable frequencies for radio communication by way of the regular layers, for April 1939 . . . ."

The predictions are used in designing new communication systems and for frequency planning and allocation purposes in order to ensure the most efficient use of radio frequencies. The new series of predictions uses computer-determined numerical mapping. Along with the maps, tables of predicted numerical map coefficients are provided for large users who have equipment enabling them to make effective use of the speed and economy of electronic computer methods in applying the predictions to communications problems. The predicted coefficients are also made available in punched-card form for more efficient computations. In addition, world maps of the ionospheric predictions are provided to the small-scale user for the manual solution of communications problems. Polar prediction maps are available for specialized high-latitude applications.



The step-by-step path that a ray takes between transmitter and receiver can now be traced by computer techniques worked out at CRPL. Ionospheric ray tracing takes the earth's magnetic field into account and allows for a "two-dimensional ionosphere" (one with the horizontal gradients along the great circle path of propagation).

Plasma Physics Research

CRPL also conducts laboratory research in plasma physics, utilizing plasmas (hot ionized gases) artificially produced in the laboratory. Microwaves in the range 3 to 70 GHz are employed to study the interactions between the particles of a plasma and electromagnetic waves traveling through the plasma, and the interactions between a moving plasma and a magnetic field. The application of microwave diagnostics to magnetoplasmas in the laboratory falls into two categories, depending on whether the frequency is greater or less than the gyromagnetic frequency of the magnetic field in the plasma.

When the frequency is greater than the gyrofrequency, the classical effects of reflection, penetration, and transmission are used for measuring such properties as the electron density, the collision frequency, the temperature, and the motion of the plasma.

One particular diagnostic tool developed to measure the plasma velocity is a multichannel reflectometer. Utilizing the Doppler principle, the novelty of the device is that two or more microwave frequencies are beamed coaxially toward the moving plasma (e.g., an approaching shock wave). When the Doppler-shifted signals are received back at the transmitter horn, they are mixed with a portion of the transmitted energy, giving a beat frequency for each channel. This technique pro-

vides a sensitive velocity measurement on each frequency, and since a different plasma density is required to reflect the separate frequencies, the structure of the shock front can be examined. In fact, measurements of shock waves in shock tubes indicate different velocities at different frequencies, while shocks from exploding wires give the same velocity for all frequencies.

The second mode of propagation, in which the frequency is less than the gyrofrequency, was first applied to laboratory plasmas by NBS personnel on the British Atomic Energy Commission device ZETA. In this mode of propagation, extremely dense plasmas can be probed by relatively low frequency microwaves. For instance, in laboratory tests the transmission of a 25-GHz microwave beam through the plasma in a theta pinch discharge (electron density of 10^{15} cm^{-3} or more) can be routinely obtained. Normally, an electron density greater than 10^{13} would reflect or absorb energy at this frequency. Propagation in this mode has also been achieved in a linear shock tube.

Tropospheric Studies

In the troposphere (from the earth's surface to a height of about 10 km), the strength and fading properties of radio waves are affected by weather, climate, and terrain. Also, a basic limitation in all areas of the atmosphere is the interference or radio noise which the signals must overcome. These properties must be estimated in order to design and assign frequencies to communication, broadcasting, and navigational facilities, and to meet urgent military needs for increased reliability, message rate, and economy of operation. Tropospheric studies are also of importance in the development of geodetic measurement systems and radio tracking and guidance systems. Microwave measurements provide powerful research tools for determining the basic characteristics of the troposphere, i.e., its turbulence, stratifications, and water vapor content.

Almost as soon as Boulder was selected for the Bureau's radio propagation laboratory, a tropospheric research program was started with transmitters on Cheyenne Mountain near Colorado Springs, Colo., and receiving stations placed on a line extending southeasterly into the plains to a distance of several hundred miles. Mobile stations were used at a number of locations including Pike's Peak and the Garden of the Gods. The program has been extended to cover a path from CRPL's Table Mesa field site near Boulder through one of the stations in the Cheyenne Mountain chain (Haswell, Colo.) to Altus in the Oklahoma panhandle. Other paths, including one in Hawaii and several in Europe and North Africa, have been established.

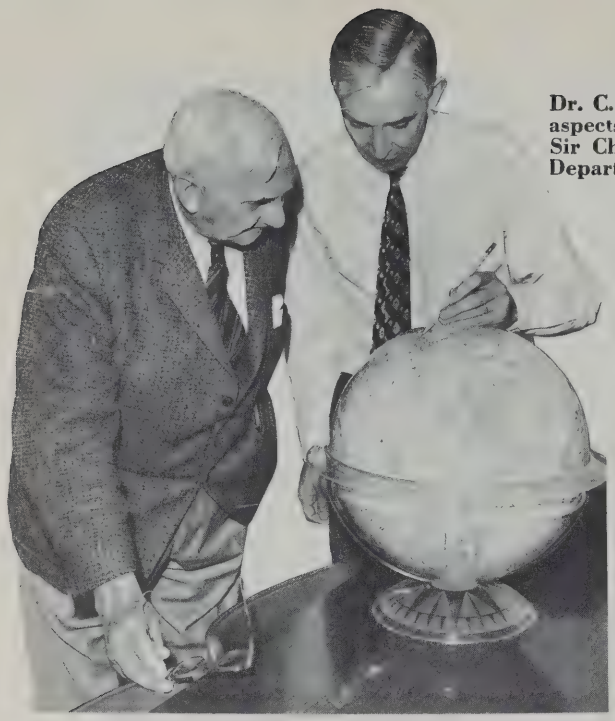
A great variety of programs has been carried out over these paths. Determination of tropospheric propagation factors for the effective allocation and use of air navigation and communication facilities is among the most important. Effects of atmospheric and meteorological variables, such as temperature and relative humidity, have also been studied. A recent experiment is the investigation of the relationship between the bandwidth of tropospheric scatter paths and the performance of multichannel, angle-modulated radio transmissions over them.

Antenna Research

A large antenna research program has operated continuously for many years. Many types of antennas, from scale models to actual full-size antennas, are studied. There are several model antenna ranges, each consisting of a turntable for antenna rotation and a target transmitter, which may be placed at varying distances from the turntable depending on the frequency being studied.

A recent installation is a tower 152 m high, on which are arrayed 10 log-periodic dipole antennas at 16-m intervals. The resultant antenna beam is electronically steerable in elevation. This supplements a horizontal

Mobile research units, consisting of trailers equipped for specific experiments, are extensively used in CRPL projects where it would be impractical or inconvenient to make permanent installations. Mobile laboratories are not new—in the photo at right, delegates to the 2d General Assembly of URSI (International Scientific Radio Union) at Washington, D.C., in 1927 "inspect the portable radio laboratory truck—used to make field measurements of the fading and intensity of radio signals throughout the country." A modern mobile laboratory is shown at left.



Dr. C. Gordon Little (*right*), Director of CRPL, discusses aspects of United States-Canadian scientific efforts with Sir Charles Wright, veteran scientist with the Canadian Department of National Defence.

array of 25 log-periodic antennas which electronically scans in azimuth. Both operate in the band of 12 to 25 MHz and are designed for high-frequency ionospheric propagation studies.

Project Mercury Forecasts

During the orbital flights of astronauts Shirra and Cooper, special efforts were made by the staff at the North Atlantic Radio Warning Service at Ft. Belvoir, Va., to keep Project Mercury headquarters informed of current and anticipated radio propagation conditions. Special forecasts of radio propagation conditions were issued ever hour during the flights, specifically for the high-frequency circuits which comprise the Project Mercury ground communications network. The forecasts were made available to the NASA Communications Director and the propagation analyst at the Goddard Space Flight Center communications center. During the periods between orbital flights, forecasts were issued by the Warning Service staff weekly, with daily updating as necessary. Reliable forecasts were made possible by associating reports of observed propagation conditions on each Project Mercury circuit with reports of observed solar, geomagnetic, and ionospheric activity occurring at the same time. This work was performed for the National Aeronautics and Space Administration.

The propagation forecasts supplied by the North Atlantic Radio Warning Service enabled the Mercury ground communications center to anticipate problems that might be encountered and select alternate frequencies or circuits to ensure unbroken communications. This reliability of communication was required in obtaining information from the astronaut and spacecraft equipment, which was telemetered to the tracking stations and relayed to the Mercury Control Center at Cape Canaveral. The same reliability was required for transmission of decisions from the Mercury Control Center to the tracking stations and the capsule itself, to ensure the safety of the astronaut and the success of the mission.

Growth of the Radio Propagation Program

The radio-wave propagation work of the Bureau dates back to the low-frequency measurements of Louis W. Austin in 1909 and publication of the Austin-Cohen formula for "range of radio-signal transmission" in 1911. This work was extended to the higher ionospheric frequencies (waves propagated by reflections from the ionosphere) after the basic discoveries of ionospheric reflections by Breit and Tuve in 1926. In the subsequent decade, the National Bureau of Standards extended the scope and extent of its ionospheric measurements and theory. Using techniques destined to be incorporated later in radar, NBS became the recognized leader in the United States in pioneering studies of radio wave propagation.

A firm, extensive program for the application of radio propagation work in the problems of radio in all its aspects was initiated when, in 1941, the National Defense Research Committee (NDRC) asked the Bureau to do research on "direction finding" and to prepare a "Radio Transmission Handbook" for the Armed Services of the country, to assist them in applying radio propagation techniques to military radio problems. In 1942, the Washington Communications Board of the Combined Chiefs of Staff took steps to organize a radio propagation laboratory and, inasmuch as the National Bureau of Standards was the leader in radio propagation work in the United States, decided to establish this laboratory, the "Interservice Radio Propagation Laboratory" (IRPL) at the Bureau. Following World War II, the work of IRPL was continued with the organization in 1946 of the Central Radio Propagation Laboratory as a scientific division of the Bureau in Washington.

In 1954 CRPL was transferred from Washington to Boulder, Colo. At that time it encompassed three divisions: Radio Propagation Physics, Radio Propagation Engineering, and Radio Standards. Later, Radio Standards was established as a separate laboratory, and in January 1959 the Radio Communication and Systems Division was formed from the engineering elements of the Radio Propagation Divisions. In 1960 CRPL was again reorganized, and is now made up of four divisions: Ionosphere Research and Propagation, Upper Atmosphere and Space Physics, Troposphere and Space Telecommunications, and Radio Systems.

When the U.S. Department of Commerce, in February 1964, announced the formation of four basic institutes under the general administration of the National Bureau of Standards, CRPL, already a "going concern," was given institute status. Also at this time, Dr. J.

Herbert Hollomon, Assistant Secretary of Commerce for Science and Technology, assigned to CRPL the responsibility for establishing and managing a system for the prediction of hazardous interplanetary radiation conditions. In his letter of assignment, Dr. Hollomon said: "As a result of the background experience and current activities of the Central Radio Propagation Laboratory in the prediction of extraterrestrial weather conditions, I am designating the National Bureau of Standards' Central Radio Propagation Laboratory as the group responsible for the management and implementation of the Department of Commerce's program in this area."

The role of CRPL is both basic and operational. Its main function is to supply the necessary basic research and development work for the use of the Government and private industry, and to provide as much of the operational information and guidance as possible in the field of applied radio propagation.

The growth of the Bureau's radio propagation program, from Dr. Austin's low-frequency measurements in 1909 to the present, can be realized only by reviewing the long list of CRPL research projects and the many worldwide radio prediction services which are presently in operation.[3]

Scientific Divisions of CRPL

Ionosphere Research and Propagation. This Division conducts and coordinates research on the propagation of radio waves as affected by the ionosphere, and on the special factors (such as solar flares) which can give rise to large departures from the normal behavior. It is also concerned with research on the nature of the media through which these radio waves are transmitted and the interaction of radio waves with the media. An important function is the preparation of predictions of radio wave propagation and warnings of solar and geophysical disturbances.

Troposphere and Space Telecommunications. Most efficient use of the radio frequency spectrum is the aim of the program in tropospheric propagation and radio noise. Attaining this objective requires a basic understanding of radio wave propagation, noise, and interference. To this end, theoretical and semi-empirical prediction methods are developed and compared with statistical samples of data on radio wave propagation and radio noise.

Radio Systems. The radio systems program provides technical information on radio propagation factors affecting design and use of radio systems. The emphasis of this work is on long-range radio transmission problems and methods of measurement for radio communication, navigation, timing, detection, and positioning systems. Standards and methods of measurement are developed for radio systems to fulfill the needs of Federal agencies and industry involved in radio communication operation and regulation.

Upper Atmosphere and Space Physics. Knowledge of the atmospheric medium is a prerequisite to the understanding of the propagation of radio waves through this medium. This knowledge is also essential in a host of applications in addition to radio communication. The program of upper atmosphere research is conducted using three experimental approaches in addition to theoretical studies. These experimental approaches are (1) ground-based geophysical observations, (2) satellite observations, and (3) laboratory experiments simulating atmospheric processes.

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[1] *The relationship between the sun and radio phenomena was first observed and correlated by Dr. J. Howard Dellinger, the first Chief of CRPL, in 1932.*

[2] *Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Annual subscription: $2.50, domestic; $3.25, foreign.*

[3] *See* 1963 Research Highlights of the National Bureau of Standards, *pp. 146–179. NBS Misc. Publ. 255, price, $1.00. Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402.*

CRPL—The Next Ten Years

by C. Gordon Little, Director, CRPL

TO PREDICT the future of an organization such as the Central Radio Propagation Laboratory for a period as long as ten years is most difficult. A comparison of today's CRPL with that of ten years ago should illustrate this point. Who in September 1954 would have predicted that, by 1964, CRPL would have doubled in size, and would have grown to an organization of four technical divisions utilizing more than 50 field sites in some 20 different countries? At that time the International Geophysical Year and satellite exploration of the upper atmosphere and space were still in the future. Who would have been farsighted enough to recognize that CRPL would be playing a major role in programs involving radar exploration of the ionosphere *from above;* or operating a super-powered ground-based radar system capable of giving electron density profiles and other geophysical data to heights of several thousand kilometers? Perhaps the rate of change of the technology of this field will decrease as the research tools become more complicated and more expensive—yet is even this likely, when one remembers the potential capabilities of masers, lasers, and space telecommunication systems?

Obviously then, one cannot predict with any accuracy the nature of CRPL and its research programs ten years in advance. Nevertheless, despite the difficulties involved, it is perhaps worthwhile to outline some of the more important trends that are now apparent. However, the evaluation and extrapolation of these trends for the next decade must be left to the reader.

CRPL's program of propagation research and services can be divided into two areas: one primarily concerned with the ionosphere, the other with the troposphere. The problems and needs relative to these two telecommunication media are very different.

First let us consider those CRPL activities that are

concerned with the ionosphere. International utilization of the ionosphere for telecommunication purposes has grown steadily during the last decade, and this growth may be expected to continue. It appears that we are about to enter an era—if we have not already done so—in which the primary limitation to increasing the total magnitude of ionospheric telecommunication lies in mutual interference, rather than in lack of understanding of the propagation processes. It seems likely that CRPL will have to pay increased attention to the problem of spectrum occupancy and spectrum utilization, and to concentrate more attention on the problem of interference.

In addition to studies directed toward increasing the total *quantity* of ionospheric telecommunication, the Laboratory will of course be concerned with studies for improving the *quality* of telecommunication; that is, for improving the performance of telecommunication systems. During the past decade, tremendous progress has been made both in describing and in understanding the gross geographic and temporal variations of the ionosphere, primarily as a result of wide application of both ground-based and satellite-borne studies of the ionosphere. During the next decade it would appear that increased attention will have to be given to the more rapid and the smaller-scale fluctuations of the ionosphere. The average behavior of the ionosphere is now relatively well understood; however, from the point of view of the telecommunication engineer, the deviations of the ionosphere from average conditions are both large and important, and require greatly improved understanding. Considerable effort will probably be given to identifying methods whereby the operator of an ionospheric telecommunication system can determine, if possible in real time, which of the frequencies available to him he should use.

CRPL has long performed a major service by the forecasting of disturbances to ionospheric radio wave propagation resulting from solar influences upon the earth's local environment in space. Recently, however, predictions of perturbation to this environment have taken on increased importance because of such programs as the Nation's man-in-space effort and the proposed high-flying supersonic aircraft. Thus it seems likely that CRPL's role in this field will expand, and that increased attention will have to be given to monitoring, understanding, and predicting solar-induced fluctuations of the earth's environment.

In regard to tropospheric telecommunication, it is clear that CRPL's research and services in this field should undergo major expansion. Traditionally the pressures for improved telecommunication capabilities (often involving increased bandwidth and improved angular resolution) have resulted in a steady extension of telecommunication usage to higher and higher frequencies. This trend is likely to continue and will be supported by systems involving masers, lasers, and space telecommunication. Already almost 90 percent of the $17 billion spent each year by this Nation on electromagnetic telecommunication through the atmosphere is for tropospheric telecommunication, yet CRPL devotes only about one-fourth of its effort to this field. (This ratio is a reflection of the original emphasis and mission of CRPL, and of the wartime Interservice Radio Propagation Laboratory from which it grew.)

The tropospheric telecommunication activities of the Nation require a considerably expanded program of tropospheric telecommunication research; it is expected that CRPL will play an increasingly important role in this research. This expansion of tropospheric research activities within CRPL has already started, and may well culminate in official recognition that CRPL should play the role of central Federal agency for propagation research and services at *all* electromagnetic frequencies, rather than just for the radio frequencies.

In conclusion, CRPL's capabilities and talents have grown steadily during the past ten years, yet the demand for our services has increased even more rapidly. These trends are likely to continue. I believe CRPL's second decade in Boulder will be marked by a stimulating and challenging series of opportunities to serve the Nation. We have been assigned responsibility for increasing the capabilities and efficiency of the Nation's many and varied telecommunication activities through the conduct of high-quality research and of efficient services. This is a challenging assignment of which we may be proud—and one which needs the best from each of us.

First Ultra-Low-Frequency Symposium Held at Boulder

SCIENTISTS from eight countries exchanged information on electromagnetic fields in the 0.001 to 30 Hz range at the first symposium held on ultra-low frequencies. The Symposium was held August 17 through 20 at the NBS Boulder Laboratories with the Bureau and the National Center for Atmospheric Research (NCAR) acting as hosts. The Symposium was co-sponsored by the American Geophysical Union, the Office of Naval Research, the Air Force Cambridge Research Laboratories, and the International Association of Geomagnetism and Aeronomy.

The International Geophysical Year program stimulated interest in the ultra-low frequencies during the years 1957 and 1958. Since then an increasing number of scientists have been studying natural signals in the ultra-low-frequency range. The Symposium in Boulder gave the scientists a chance to re-evaluate research already done, summarize the work, and define active frontiers of study. The Symposium was conducted in three major sessions with invited speakers on the subjects of environment, signal sources, and observations. A fourth session was a forum where selected papers from delegates were presented. Speakers at the Symposium included scientists from Japan, Nigeria, Canada, England, Germany, Sweden, and the United States.

Atmospheric Transmission at Infrared Frequencies

THE BUREAU has recently undertaken a program to compute the characteristics of radiative transmission through the atmosphere at infrared frequencies. The calculated theoretical transmission spectra [1] will provide a basis on which to intercompare all available observed transmission data in the infrared region. In addition to their vital role in space communication, these data are fundamental to the solution of problems concerning missile detection, radiative energy transfer, and astronomical "seeing."

Results obtained thus far on the determination of absorption by water vapor and carbon dioxide are in excellent agreement with observations. The program is being conducted by David M. Gates, Robert F. Calfee, and David W. Hansen* of the NBS Central Radio Propagation Laboratory at Boulder, Colo., and William S. Benedict of the NBS Institute for Basic Standards in Washington, D.C. The work is supported by the Advanced Research Projects Agency.

It long has been evident that the only fundamental approach to the solution of problems of atmospheric transmission at infrared frequencies would be through an understanding of the infrared spectrum in great detail. For some time the enormous complexities of this spectrum discouraged such an effort, but needs of the Government and industry necessitated that an attempt be made. Fortunately, the advent of large-scale automatic electronic computers has made the formidable task of computing transmissions for given atmospheric conditions a manageable one.

The radiative exchange of energy in the earth's atmosphere takes place primarily by means of complex absorptions at infrared wavelengths in the vibration-rotation bands of water vapor, carbon dioxide, and ozone, three minor constituents of the atmosphere. These absorption bands are composed of many thousands of lines—essentially the fingerprints of the molecule—each of which is the result of a quantum transition. Within the last few years knowledge concerning the quantum mechanics of these molecules has progressed enormously through the analysis of high-resolution spectra produced in the laboratory.

Because many excellent results have been obtained from experimental observations and analyses of the water-vapor spectrum, study of the 2.7 μ water-vapor absorption band was undertaken first. This band alone contains more than 4400 lines of strength sufficient to be considered. The machine calculation of position, strength, half-width, line shape, and dependence upon pressure, temperature, and absorbing gas concentration had to be programmed for every one of these lines. The infinite-resolution theoretical transmission at any frequency is then the sum of the individual transmissions by outlying areas of many neighboring lines and the individual transmission of the nearest line. Typical examples of this theoretical transmission spectrum were calculated for given conditions of pressure, temperature, and absorbing gas concentration.

In order to compare the theoretical spectra with observed spectra, it was then necessary to degrade the theoretical spectra by a suitable instrument factor. A triangular slit function was programmed for this purpose. When these calculated spectra are compared with high-altitude absorption spectra obtained in jet aircraft flying at 45,000 ft, excellent agreement is found—agreement so good that every single absorption line due to water vapor can be accounted for. Important comparisons have also been made with transmissions observed horizontally above the sea surface. Further comparisons will be made by the Bureau and other agencies at horizontal paths, including laboratory long-path cells and observations from peak to peak high in the Bolivian Andes.

Nearly completed, in addition to the 2.7 μ water-vapor band, are studies of the 1.9 μ water-vapor and the 2.7 μ carbon dioxide bands. In the near future, the 1.4, 1.1, and 6.3 μ water-vapor bands will be examined, as will the 2.0, 4.3, and 14.0 μ carbon dioxide bands and the far infrared pure rotation band of water vapor. The results are being published as a series of NBS monographs and as papers in the open literature.

[1] *For further technical details, see* Line parameters and computed spectra for water vapor bands at 2.7 μ, *David M. Gates, Robert F. Calfee, David W. Hansen, and W. S. Benedict, NBS Mono. 71 (1964). For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Price: $2.00.*

Robert F. Calfee points out the extremely high resolution in theoretical infrared transmission spectra calculated at CRPL. The two lower figures show the resolution obtained when an instrument factor has been applied to produce a spectrum comparable with that obtained from a typical spectrometer.

*Present address: Naval Weather Center, Point Mugu, Calif.

System for Recording Phase and Amplitude Variations

AN IMPROVED system for recording the relative phase and amplitude of frequency-stabilized low frequency (LF) and very low frequency (VLF) transmission has been designed by Arthur H. Diede, of the Central Radio Propagation Laboratory. The improved versatility and ease of maintenance of the system are achieved by the use of modular construction and plug-in printed circuit boards. This type of construction enables the system to meet any anticipated requirements for coherent measurements in the LF and VLF region. The very low power dissipation of the transistor circuits increases the reliability and long-term stability of the coherent system. The Advanced Research Projects Agency of Washington, D.C., supported this work.

The system uses a coherent detection technique in which the received signal is compared with a voltage derived from a highly stable 100-kHz reference oscillator. The basic operational functions of the system are as follows: the received signal of frequency f is converted to an IF signal of 1 kHz using a local oscillator (frequency of $f-1$ kHz) derived from the reference oscillator by means of the VLF synthesizer and multiplier units. The 1-kHz signal from the VLF receiver is then compared in two coherent detectors with a 1-kHz reference voltage, also derived from the reference oscillator by means of the VLF synthesizer. Since the 1-kHz and the local-oscillator signals are both phase-locked to the reference oscillator, the phase difference between the 1-kHz reference and the 1-kHz IF signal is a measurement of both the phase variation introduced by the propagation medium and that due to the frequency difference between the transmitter frequency standard and the local reference oscillator.

A voltage proportional to the cosine of the phase difference is produced by the phase detector. This voltage activates a servosystem which changes the phase of the 1-kHz reference in such a way as to give a minimum output voltage from the phase detector. The resulting change in phase of the reference voltage is thus a measurement of the phase difference between the received signal and local reference oscillator. This change is recorded on a special recorder.

A measurement of the relative field strength is obtained by comparing, in the amplitude detector, the 1-kHz signal from the VLF receiver with a second 1-kHz reference voltage from the phase generator. This reference voltage differs 90° from the 1-kHz reference voltage used in the phase detector. The output voltage of the amplitude detector will therefore be proportional to the received signal amplitude as long as the servosystem is tracking the received signal. This output voltage is recorded on a second channel of the recorder as the signal amplitude.

The VLF synthesizer also produces a phase-stable reference voltage at any desired signal frequency which is a multiple of 25 Hz. This voltage is used to calibrate the entire system, excluding the antenna. The reference voltage is applied to the VLF receiver in place of the received signal. A calibrated attenuator allows an accurate measurement to be made of the applied reference voltage. The system phase and amplitude response characteristics can therefore be measured.

This improved recording system will greatly aid research in phase and amplitude of VLF and LF standard-frequency transmissions.

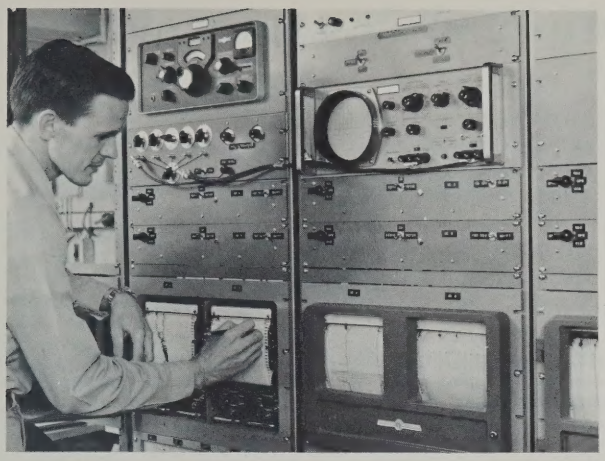
VLF Phase Recording in Antarctica

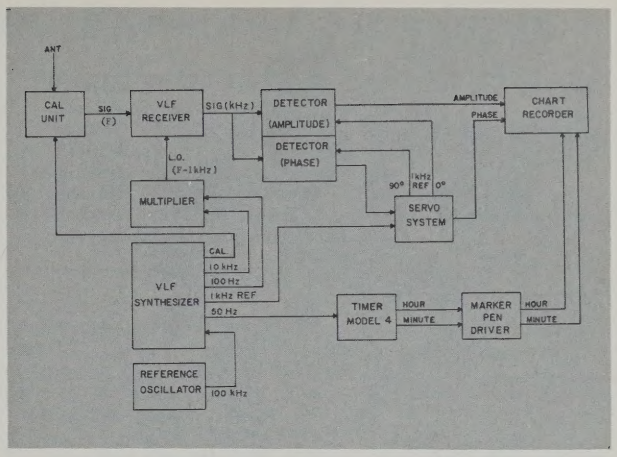
MEASUREMENTS of the phase and amplitude of manmade VLF (very low frequency) transmissions are made at Byrd Station in Antarctica in a joint program conducted by the NBS Central Radio Propagation Laboratory (CRPL) and the Stanford University Radio Science Laboratory. This program is supported by the National Science Foundation and the Advanced Research Projects Agency.

The VLF recording equipment designed and constructed by Arthur H. Diede of CRPL (see preceding article) has been installed at Byrd Station by Ronald L. Sefton and Robert B. Flint, of the Stanford University staff. It is being used to record variations in VLF transmissions originating in the Northern Hemisphere.

The signals being observed at Byrd Station are of special interest because they are propagated across the geomagnetic equator. Thus the data, it is believed, will shed light on variations which are characteristic of the ionosphere above the equator.

Eights is the Antarctic station paired with Baie St. Paul, Canada, for conjugate-point studies along the same geomagnetic field line ($L=4$). The concept of conjugate-point studies is that observations made at opposite ends of a given line of the geomagnetic field permit the investigation of geophysical phenomena such as VLF emission, whistlers, and absorption events which are associated with electromagnetic waves or energetic particles guided along the magnetic field line.





Left: **Arthur Diede inspects eight-channel equipment developed at CRPL for recording the phase and amplitude of VLF and LF standard frequency transmissions. The system has been installed at Byrd Station, Antarctica, for recording variations in VLF transmissions originating in the Northern Hemisphere.** *Right:* **Block diagram of equipment.**

Some of the VLF signals received at Byrd Station pass through a geomagnetically anomalous region off the east coast of South America. By comparing these signals with those which have not passed through this area, it may be possible to observe effects on the lower ionosphere which are due to the presence of the geomagnetic anomaly.

Byrd Station is relatively close to the magnetic conjugate points of at least two VLF transmitters, those of the U.S. Navy stations NSS (Annapolis, Md.) and NAA (Cutler, Me.). It is therefore expected that signals from these stations will be received by means of propagation in the "whistler mode," as well as by the normal earth-ionosphere waveguide mode. The observations are expected to yield informative comparisons of the two modes.

In addition, the Byrd observations will supplement similar observations being made concurrently in the Northern Hemisphere. Observations in both hemispheres will be particularly useful in studies of normal diurnal phase variations as well as those associated with geomagnetic disturbances, solar proton events, and solar flares.

Mapping High-Latitude Ionospheric Absorption

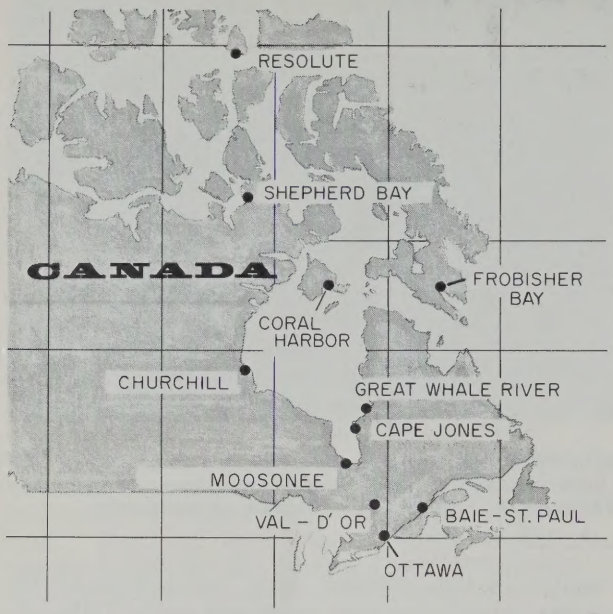
SCIENTISTS at the Bureau's Central Radio Propagation Laboratory have developed a method for mapping the extent and movement of absorbing patches in the ionosphere, using an electronic computer. Data from 10 riometer stations located in Canada between 60° and 90° north magnetic latitude and recording simultaneously are fed into the computer. The computer printout indicates the occurrence of absorption with respect to time at the various latitudes and provides an effective contour map of the absorption event.

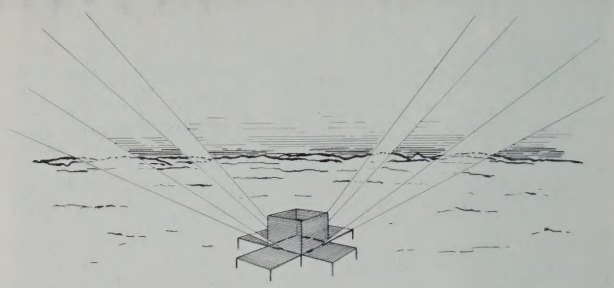
H. J. A. Chivers, Chief of the High Latitude Ionospheric Physics Section, is presently evaluating data obtained by this method for the large absorption events of Sept. 26–29, 1963. The results indicate a general movement of the absorbing regions both from south to north and from north to south as the event continues. If a predictable pattern should develop, the data will be valuable in radio propagation forecasts for high-latitude radio paths.

In order to obtain data from enough stations to secure these results, an agreement was obtained for data to be provided from seven stations operated by the Defence Research Telecommunications Establishment of Canada. These data are analyzed along with those from the Bureau's three conjugate-point stations in Canada.

Ray Montalbetti of the Defence Research Telecommunications Establishment is in charge of the seven Canadian riometer stations in the network. From north to south, the stations are located at Resolute, Coral Harbour, Churchill, Cape Jones, Moosenee, Val d'Or, and Ottawa. All except the Cape Jones station are vertical recording stations, recording the amount of absorption directly overhead. Cape Jones has a three-way system which simultaneously measures to the north, overhead, and to the south.

The three Bureau stations in the program are located at Frobisher Bay, Great Whale River, and Baie St. Paul. The first two have only vertical riometers. The Baie St. Paul station has an elaborate system which measures absorption at five separate locations simultaneously. In addition to the conventional vertical antenna for overhead measurement, there is a four-sided corner reflector antenna which observes the absorption in four areas located at 90-deg increments of the compass





Above: **Artist's impression of the new antenna at the CRPL conjugate point field site at Baie St. Paul, Canada. The antenna looks in four directions—to the north, south, east, and west—and measures the absorption of radio waves by the ionosphere in those directions.**

Left: **Locations of the 10 riometer stations gathering data for absorption study are shown. The additional station, Shepherd Bay, is not presently part of the chain.**

and 45° above the surface of the earth. The antenna, which has been in operation since July 1963, was designed by Louis D. Breyfogle of the Ionospheric Radio Astronomy Section. His design was based on the work of a team from CRPL under the direction of C. Gordon Little. The construction was carried out by Mark Andrews of the Upper Atmosphere and Space Physics Division with the help of local workmen.

In addition to the cooperation between the United States and Canada in sharing data from their separate stations, the assistance of the Canadian government in securing sites for the Bureau stations and in manning the Frobisher Bay station has been noteworthy, according to Dr. Chivers. Such cooperative programs result in greater use of the data from the stations of both countries and make a more comprehensive coverage possible in the most economical way.

Fourth Book in Electromagnetic Wave Series

Ionospheric Sporadic–E is the title of a book edited by Ernest K. Smith of the NBS Central Radio Propagation Laboratory and Samadi Matsushita of the High Altitude Observatory of the University of Colorado, both at Boulder, Colo. The fourth in the International Series of Monographs on Electromagnetic Waves published by Pergamon Press, New York, N.Y., and Oxford, England, this book is a survey of sporadic–*E* ionization. It presents experimental work in the field, analyses of data, and theroretical approaches to the structure and physical mechanisms in the medium.

Dr. Smith and Dr. Matsushita not only edited this volume of monographs, but also are authors of some of the articles contained in it. Other contributors from the staff of the NBS Boulder Laboratories include James R. Wait (also an editor in this series), Kenneth Bowles, Walter Chadwick, Robert Cohen, Joseph DeGregorio, James Finney, Sanford Gladden, Karl Kildahl, Robert Knecht, Hope Leighton, Rhoda McDuffie, Gerald Ochs, and Alan Shapley. Among the contributions are some dealing with measurement of vertical incidence obtained under an International Geophysical Year program organized by Dr. Smith for the National Science Foundation.

The contents of this book represent the joint efforts of eight research installations and seven colleges and universities, from nine countries. This is indicative of the growing trend for scientific communities to transcend national boundaries.

Publications of the National Bureau of Standards

Periodicals

Technical News Bulletin, Vol. **48**, No. 8, August 1964. 15 cents. Annual subscription: $1.50; 75 cents additional for foreign mailing. Available on a 1-, 2-, or 3-year subscription basis.

CRPL Ionospheric Predictions for November 1964. Three months in advance. Number 20, issued August 1964. 15 cents. Annual subscription: $1.50; 50 cents additional for foreign mailing. Available on a 1-, 2-, or 3-year subscription basis.

Journal of Research of the National Bureau of Standards

Section A. Physics and Chemistry. Issued six times a year. Annual subscription: Domestic, $4; foreign, $4.75. Single copy, 70 cents.

Section B. Mathematics and Mathematical Physics. Issued quarterly. Annual subscription: Domestic, $2.25; foreign, $2.75. Single copy, 75 cents.

Section C. Engineering and Instrumentation. Issued quarterly. Annual subscription: Domestic, $2.25; foreign, 2.75. Single copy, 75 cents.

Section D. Radio Science. Issued monthly. Annual subscription: Domestic, $9; foreign, $11.50. Single copy, $1.00.

Current Issues of the Journal of Research

J. Res. NBS **68B** (*Math. and Math. Phys.*), *No. 3* (*July–Sept. 1964*).

Generation and composition of functions. A. J. Goldman.

Thermodynamics of perfect elastic fluids. B. Bernstein, E. A. Kearsley, and L. J. Zapas.

Zeros of polynominals in several variables and fractional order differences of their coefficients. B. Mond and O. Shisha.

Theory of radiation from sources immersed in anisotropic media. J. R. Wait.

J. Res. NBS **68C** (*Eng. and Instr.*), *No. 3* (*July–Sept. 1964*).

Response of highly precise balances to thermal gradients. L. Macurdy.

A direct-reading two-knife 50-pound balance of high precision suitable for State weights and measures laboratories. H. E. Almer, H. A. Bowman, M. W. Jensen, L. B. Macurdy, H. S. Peiser, and B. Wasko.

Wave front shearing prism interferometer. J. B. Saunders.

A new high-resolution small-angle x-ray camera. H. Brumberger and R. Deslattes.

Experimental determination of air drag on a textile yarn struck transversely by a high-velocity projectile. J. C. Smith, C. A. Fenstermaker, and P. J. Shouse.

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Symposium on Signal Statistics, Seattle, Washington, U.S.A., December 6–7, 1963:

Signal statistics, yesterday and today. F. L. H. M. Stumpers.

Rayleigh distribution and its generalizations. P. Beckmann.

Some nonlinear problems arising in the study of random processes. M. Rosenblatt.

An approach to empirical time series analysis. E. Parzen.

Effect of linear and nonlinear signal processing on signal statistics. A. V. Balakrishnan.

Random volume scattering. H. Bremmer.

Phase fluctuation statistics. J. B. Smyth.

Current topics in the stochastic theory of radiation. F. J. Zucker.

On the intensity distribution

$$\frac{2R}{\sqrt{\alpha\beta}} \exp\left[-\frac{R^2}{2}\left(\frac{1}{\alpha}+\frac{1}{\beta}\right)\right] I_0\left(\frac{R^2}{2}\left[\frac{1}{\beta}-\frac{1}{\alpha}\right]\right)$$

and its application to signal statistics. M. Nakagami.

Statistical inference for Rayleigh distributions. M. M. Siddiqui.

A probabilistic approach to the problem of large antenna arrays. Y. T. Lo.

Influence of data processing on the design and communication of experiments. S. W. Golomb.

Spectral measurement techniques in planetary radar. G. Pettengill.

Quantum statistics and lasers. J. P. Gordon.

Statistics of random surfaces. I. Kay and P. Swerling.

Modified gaussian distributions for slightly nonlinear variables. M. S. Longuet-Higgins.

Other NBS Publications

Line parameters and computed spectra for water vapor bands at 2.7μ, D. M. Gates, R. F. Calfee, D. W. Hansen, and W. S. Benedict, NBS Mono. 71 (Aug. 3, 1964), $2.00.

An engineering method for calculating protection afforded by structures against fallout radiation, C. Eisenhauer, NBS Mono. 76 (July 2, 1964), 20 cents.

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Patents Granted on NBS Inventions

The following U.S. Patents have recently been granted on NBS inventions and, except as noted, are assigned to the United States of America as represented by the Secretary of Commerce.

3,122,076 February 25, 1964. Intermittent action camera. Gifford Hefley, Robert F. Linfield, Robert H. Doherty, and Earl L. Berger (Air Force).

3,123,821 March 3, 1964. Proximity fuse with two oscillators. Robert D. Huntoon (Army).

3,124,747 March 10, 1964. Coaxial thermal voltage converter. Francis L. Hermach.

3,131,348 April 28, 1964. Coulometric titration coulometer. John K. Taylor and Stanley W. Smith.

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